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VOLUME 10 MARCH, 1934 NUMBER 3

FURTHER OBSERVATIONS ON THE POLLEN CONSTANCY OF BEES[1]

BY W. H. BRITTAIN[2] AND DOROTHY E. NEWTON[3]

Abstract

Further studies of the pollen constancy of hive bees and the wild bee visitors to apple blossoms, in continuation of those previously published (1, 2), are reported. Only hive bees and various *Andrena* spp. appeared in significant numbers in this study. The latter show a much lower degree of constancy than the former, confirming previous work. The wide difference between the complex of insect pollinators at Macdonald College and that of Kings County, Nova Scotia, is discussed. The highly polytrophic character of the common insect pollinators of the apple is emphasized.

Introduction

In previous papers (1, 2) the results of detailed studies on apple pollination, with regard to insect pollinators, have been discussed. The hive bee has, in comparison with solitary wild bees, certain advantages as an orchard pollinator. It has longer working hours and greater efficiency under unfavorable weather conditions; it increases rapidly and can be artificially distributed. It has been pointed out that, though the hive bee has the advantages mentioned, the small wild bees of the genera *Halictus* and *Andrena* have certain other advantages. In some fruit growing regions nesting places are abundant, and these are not necessarily reduced by modern agricultural practices, since roadsides, rough pastures, steep banks and similar situations may offer suitable sites. A minor point in favor of the solitary bees is their method of carrying pollen, which is more likely to result in cross-pollination of the flower than the more specialized mode of *Apis* or *Bremus*. As pointed out by Professor Cockerell (*in litt.*), *Halictus*, contrary to customary definition, has a scopa-like structure on the abdomen, and in some species, especially some of the Australian forms, it is quite well developed. The more specialized habits of the hive bee workers with respect to the division of labor were also considered to be an adverse factor in that the numbers of workers available for pollination were reduced.

[1] *Manuscript received December 13, 1933.*
Contribution from Macdonald College, Macdonald College Post Office, Que.
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One point in which superiority has been generally claimed for the hive bee has been its supposed greater constancy to its flower. In studies made in 1932 (2), however, no marked superiority of the hive bee over *Halictus* was demonstrated, though *Andrena* did appear to be noticeably less constant than either *Apis* or *Bremus*.

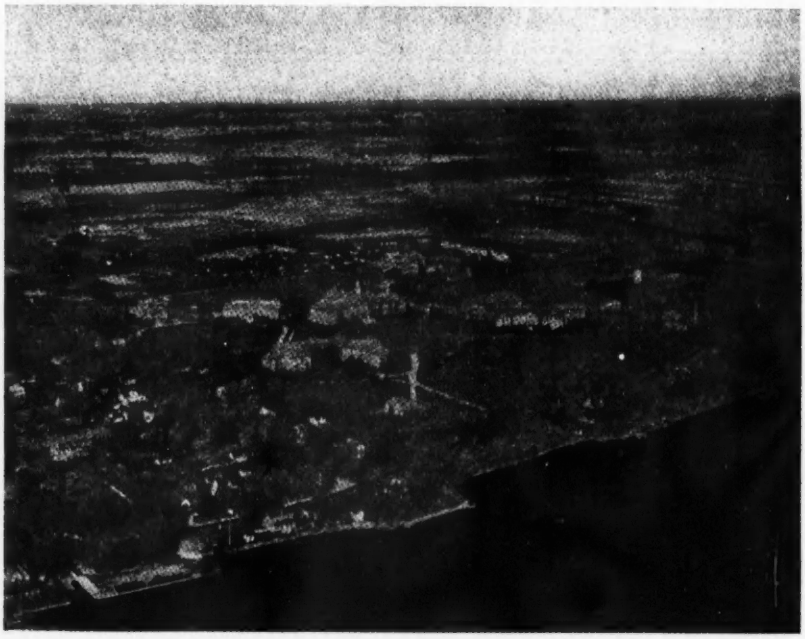


FIG. 1. *Aerial view of Macdonald College campus showing plant distribution, nesting sites and other ecological features. (Published by permission of Fairchild Aerial Surveys Company of Canada, Ltd.)*

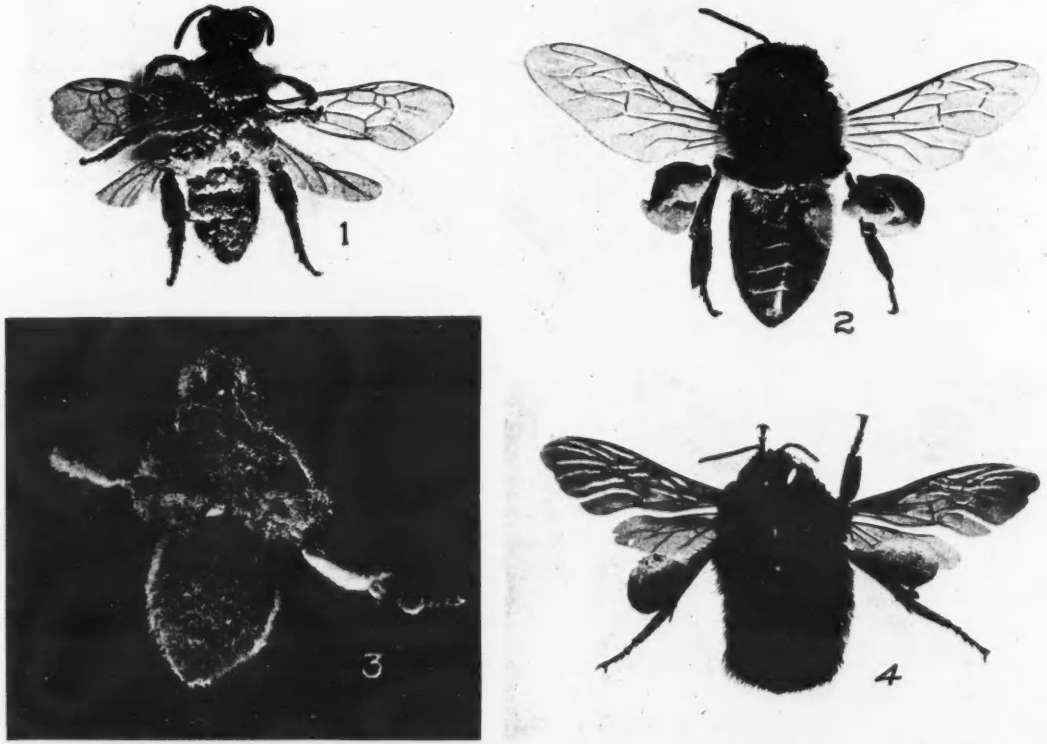
The present study, confined to Macdonald College, is a continuation of previous work on this subject. The main collections were made on apples, supplemented by smaller ones from various plants flowering at the same time or just subsequent to the apple.

Character of Locality Studied

Since a description has been given (1) of the various localities where previous studies were made it is necessary only to state that at Macdonald College there was available a 30-acre apple orchard, together with a profusion of flowering shrubs and herbs, whereas at all the observation points in Nova Scotia, apple greatly predominated. Fig. 1 indicates the nature of the territory where the present studies were made.

Insects Involved

It is of interest to note the species involved in apple pollination at Macdonald College, as compared with those concerned in this work in Kings



Ventral view of bees showing pollen carrying apparatus. 1. Halictus coriaceus Smith. 2. Apis mellifica L. 3. Closer view of the preceding, showing pollen attached to body hairs. 4. Bremus fervidus Fab.

PLATE I

County, Nova Scotia. In both areas the chief agents, in addition to the hive bee, consisted of solitary bees of the genera *Halictus* and *Andrena*. Diptera, chiefly Syrphidae, were of minor importance, and Bremidae comparatively scarce. A list of the Nova Scotia species has already been published (2), but further study has necessitated certain changes in the identification and synonomy of the species. Mr. C. E. Atwood, who has made a critical study of the Nova Scotia Andrenidae has revised the list and also determined the bees collected at Macdonald College in the present study. These lists are presented in Table I. In the list of species taken at Macdonald College, Diptera and Bremidae have been omitted as they played a very minor role.

TABLE I

LIST OF APPLE POLLINATORS IN NOVA SCOTIA AND AT MACDONALD COLLEGE

Nova Scotia		Macdonald College	
Halictus spp.	*Andrena* spp.	*Halictus* spp.	*Andrena* spp.
viridatus Lov. *(a)*	*carlini* Ckll.	*macoupinensis* Robt.	*annae* Ckll.
leucozonius (Schrank) *(b)*	*vicina* Sm.	*provancheri* D.T.	*carlini* Ckll.
zonulus Sm. *(c)*	*wilkella* Kby.	*sparsus* Robt.	*crataegi* Robt.
rubicundus (Christ.) *(d)*	*crataegi* Robt.	*viridatus* Lov.	*flavoclypeata* Sm. *(f)*
arcuatus Robt.	*rugosa* Robt.	*zonulus* Sm.	*forbesii* Robt.
cressonii Robt.	*milwaukeensis* Graen.		*mariae* var. *concolor* Robt.
provancheri D.T.	*bradleyi* Vier.		*miranda* Sm.
pilosus Sm.	*mariae* var. *concolor* Robt. *(e)*		*nasoni* Sm.
foxii Robt.	*miranda* Sm.		*lata* Vier.
pectoralis Sm.	*thaspii* Graen.		*persimulata* Vier.
coriaceus Sm.			*regularis* Mall.
			vicina Sm.
			wilkella Kby.

(a) H. smilacinae Robt. = *planatus* Lov. = *versans* Lov. *of former list (1). The writers' material agrees with authentically named specimens of viridatus. Should type material of smilacinae prove to be cospecific, the latter would have priority. (b) H. craterus of former list, in part. (c) H. craterus* Lov. *(d) H. lerouxii of list. (e) A. weedi of list. (f). A. bipunctata Cresson.*

Food Habits of Bees

The foregoing study opens up some interesting questions regarding the food habits of *Halictus* and *Andrena*, particularly the apple pollinators. Cockerell (*in litt.*) states that it may be laid down as a general rule that, *when a cultivated plant is not native in a region it will attract only the polytrophic species*. He states that in America the various cacti are noteworthy for their interesting bee visitors, largely *Diadasia* and *Lithurgus*, but, in South Africa, where *Opuntia* has overrun the country, it is useless to look for bees in the flowers.

It is of interest to examine the writers' host records in the light of the foregoing. Results of pollen analyses made at Macdonald College only are shown in Tables II and III. The following list shows the chief plant genera on which captures were made, and Tables IV and V indicate the bee species

taken on each. All available records from Kings County, Nova Scotia, and Macdonald College are included, but it should be noted that at Macdonald College little collecting was done except on apple. In Nova Scotia it was not possible to do any extensive collecting previous to apple bloom, and hence few records are available from the early spring flora. Later collecting was extensive though not exhaustive, and a more intensive search would doubtless yield additional species. Numerous species, represented in most cases by single specimens, have not been included because of uncertain identification.

LIST OF PLANT GENERA VISITED BY *Andrena* AND *Halictus*

1. *Achillea*
2. *Amelanchier*
3. *Amorpha*
4. *Apocynum*
5. *Aralia*
6. *Arctium*
7. *Aster*
8. *Brassica*
9. *Centaurea*
10. *Cerastium*
11. *Chrysanthemum*
12. *Cichorium*
13. *Cirsium*
14. *Cornus*
15. *Crataegus*
16. *Daucus*
17. *Diervilla*
18. *Epilobium*
19. *Fragaria*
20. *Hieracium*
21. *Kalmia*
22. *Ledum*
23. *Leontodon*
24. *Narcissus*
25. *Prunus*
26. *Pyrus malus**
27. *Pyrus* spp.*
28. *Raphanus*
29. *Rhododendron*
30. *Rhus*
31. *Rosa*
32. *Rubus*
33. *Salix*
34. *Solidago*
35. *Sonchus*
36. *Spergula*
37. *Stellaria*
38. *Syringa*
39. *Taraxacum*
40. *Trifolium*
41. *Vaccinium*
42. *Veronica*
43. *Viburnum*
44. *Philadelphus*

TABLE II

POLLEN ANALYSIS OF BEES AT MACDONALD COLLEGE—MAY 22-JUNE 3, 1933

No. examined	Bee species	Host	Pollen species
40	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus*
1	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Lonicera*
2	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Prunus*
1	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Spiraea*
16	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Taraxacum*
4	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Taraxacum (1)*
2	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Taraxacum (2)*
2	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Taraxacum (3)*
1	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Tulipa*
1	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Caragana; Taraxacum*
1	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Lonicera; Prunus*
2	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Spiraea; Taraxacum*
1	*Apis mellifica* L.	*Pyrus malus*	*Pyrus malus; Prunus; Taraxacum; Syringa*
2	*Apis mellifica* L.	*Syringa vulgaris*	*Syringa*
1	*Apis mellifica* L.	*Syringa vulgaris*	*Syringa; Lonicera*
1	*Apis mellifica* L.	*Syringa vulgaris*	*Syringa; Lonicera; Taraxacum*
2	*Apis mellifica* L.	*Berberis vulgaris*	*Berberis*
4	*Apis mellifica* L.	*Berberis vulgaris*	*Berberis; Caragana (4)*
16	*Apis mellifica* L.	*Lonicera*	*Lonicera*
1	*Apis mellifica* L.	*Lonicera*	*Lonicera (5)*
1	*Apis mellifica* L.	*Lonicera*	*Lonicera; Berberis*
1	*Apis mellifica* L.	*Lonicera*	*Lonicera; Pyrus malus*
1	*Apis mellifica* L.	*Lonicera*	*Lonicera; Viburnum*
3	*Apis mellifica* L.	*Caragana arborescens*	*Caragana*
2	*Apis mellifica* L.	*Caragana arborescens*	*Caragana; Lonicera*
1	*Apis mellifica* L.	*Caragana arborescens*	*Caranga; Viburnum*
1	*Apis mellifica* L.	*Caragana arborescens*	*Caragana; Berberis; Viburnum; Cornus*
1	*Apis mellifica* L	*Caragana arborescens*	*Caragana; Lonicera; Viburnum; Pyrus malus*
1	*Apis mellifica* L.	*Cornus paniculata*	*Cornus; Berberis*

**Material from Pyrus malus was separated from that collected on other species of Pyrus.*

TABLE II—*Continued*

POLLEN ANALYSIS OF BEES AT MACDONALD COLLEGE—MAY 22-JUNE 3, 1933

No. examined	Bee species	Host	Pollen species
1	*Apis mellifica* L.	*Cornus paniculata*	*Caragana; Prunus*
1	*Apis mellifica* L.	*Centaurea montana*	*Centaurea (6)*
1	*Andrena* sp.	*Pyrus malus*	*Pyrus malus; Taraxacum (7)*
1	*Andrena* sp.	*Pyrus malus*	*Pyrus malus; Taraxacum; Prunus*
1	*Andrena* sp.	*Pyrus malus*	*Pyrus malus; Taraxacum; Spiraea*
4	*Andrena annae* Ckll.	*Pyrus malus*	*Pyrus malus*
3	*Andrena annae* Ckll.	*Pyrus malus*	*Pyrus malus; Taraxacum*
1	*Andrena annae* Ckll.	*Pyrus malus*	*Pyrus malus; Ribes*
1	*Andrena annae* Ckll.	*Pyrus malus*	*Pyrus malus; Spiraea*
1	*Andrena annae* Ckll.	*Pyrus malus*	*Pyrus malus; Taraxacum; Spiraea*
1	*Andrena annae* Ckll.	*Pyrus malus*	*Pyrus malus; Taraxacum; Syringa*
1	*Andrena annae* Ckll.	*Pyrus malus*	*Pyrus malus; Prunus; Ribes*
1	*Andrena annae* Ckll.	*Pyrus malus*	*Taraxacum*
1	*Andrena carlini* Ckll.	*Pyrus malus*	*Pyrus malus; Prunus*
1	*Andrena carlini* Ckll.	*Pyrus malus*	*Pyrus malus; Taraxacum*
7	*Andrena crataegi* Robt.	*Pyrus malus*	*Pyrus malus*
1	*Andrena crataegi* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum (8)*
1	*Andrena crataegi* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum; Caragana*
1	*Andrena crataegi* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum; Prunus*
1	*Andrena crataegi* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum; Ribes*
1	*Andrena crataegi* Robt.	*Cornus paniculata*	*Cornus; Caragana*
1	*Andrena crataegi* Robt.	*Lonicera tatarica*	*Spiraea; Caragana*
2	*Andrena flavoclypeata* Sm.	*Pyrus malus*	*Pyrus malus; Taraxacum*
1	*Andrena flavoclypeata* Sm.	*Cornus paniculata*	*Pyrus malus*
3	*Andrena forbesii* Robt.	*Pyrus malus*	*Pyrus malus*
1	*Andrena forbesii* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum*
1	*Andrena forbesii* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum (9)*
1	*Andrena mariae* var. *concolor* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum*
1	*Andrena mariae* var. *concolor* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum; Prunus*
1	*Andrena miranda* Sm.	*Pyrus malus*	*Pyrus malus*
1	*Andrena miranda* Sm.	*Pyrus malus*	*Pyrus malus; Caragana*
1	*Andrena miranda* Sm.	*Pyrus malus*	*Pyrus malus; Taraxacum*
1	*Andrena miranda* Sm.	*Pyrus malus*	*Pyrus malus; Viburnum*
1	*Andrena miranda* Sm.	*Pyrus malus*	*Pyrus malus; Taraxacum; Spiraea*
3	*Andrena nasoni* Robt.	*Pyrus malus*	*Pyrus malus*
2	*Andrena nasoni* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum*
1	*Andrena nasoni* Robt.	*Pyrus malus*	*Pyrus malus; Taraxacum; Caragana (10)*
1	*Andrena lata* Vier.	*Pyrus malus*	*Pyrus malus*
1	*Andrena lata* Vier.	*Pyrus malus*	*Pyrus malus; Taraxacum; Caragana (11)*
1	*Andrena lata* Vier.	*Spiraea vanhouttei*	*Pyrus malus; Spiraea*
1	*Andrena persimulata* Vier.	*Cornus paniculata*	*Cornus*
1	*Andrena regularis* Mall.	*Pyrus malus*	*Pyrus malus; Taraxacum*
19	*Andrena vicina* Sm.	*Pyrus malus*	*Pyrus malus*
1	*Andrena vicina* Sm.	*Pyrus malus*	*Pyrus malus; Caragana*
1	*Andrena vicina* Sm.	*Pyrus malus*	*Pyrus malus; Prunus*
7	*Andrena vicina* Sm.	*Pyrus malus*	*Pyrus malus; Taraxacum*
1	*Andrena vicina* Sm.	*Pyrus malus*	*Pyrus malus; Taraxacum (12)*
1	*Andrena vicina* Sm.	*Pyrus malus*	*Pyrus malus; Taraxacum (13)*
1	*Andrena vicina* Sm.	*Pyrus malus*	*Pyrus malus; Taraxacum; Prunus*
1	*Andrena vicina* Sm.	*Pyrus malus*	*Pyrus malus; Taraxacum; Caragana*
1	*Andrena vicina* Sm.	*Pyrus malus*	*Pyrus malus; Prunus; Spiraea*
1	*Andrena vicina* Sm.	*Spiraea vanhouttei*	*Caragana; Berberis*
1	*Andrena vicina* Sm.	*Berberis vulgaris*	*Berberis; Caragana; Tulipa*
1	*Andrena vicina* Sm.	*Berberis vulgaris*	*Berberis; Caragana; Lonicera*
1	*Andrena wilkella* Kby.	*Berberis vulgaris*	*Lonicera; Narcissus*
1	*Andrena wilkella* Kby.	*Pyrus malus*	*Pyrus malus; Taraxacum; Viburnum*
1	*Andrena wilkella* Kby.	*Spiraea vanhouttei*	*Berberis; Caragana; Spiraea*

TABLE II—*Concluded*

POLLEN ANALYSIS OF BEES AT MACDONALD COLLEGE—MAY 22-JUNE 3, 1933

No. examined	Bee species	Host	Pollen species
1	*Andrena wilkella* Kby.	*Spiraea vanhouttei*	*Cornus; Spiraea; Pyrus malus (14)*
1	*Andrena wilkella* Kby.	*Caragana arborescens*	*Caragana; Narcissus; Pyrus malus*
1	*Halictus macoupinensis* Robt.	*Pyrus malus*	*Pyrus malus*
1	*Halictus provancheri* D.T.	*Pyrus malus*	*Pyrus malus*
1	*Halictus provancheri* D.T.	*Pyrus malus*	*Pyrus malus; Tulipa*
1	*Halictus provancheri* D.T.	*Cornus paniculata*	*Cornus; Taraxacum; Viburnum*
1	*Halictus* sp.	*Pyrus malus*	*Pyrus malus; Spiraea*
1	*Halictus viridatus* Lov.	*Cornus paniculata*	*Pyrus malus; Caragana; Syringa*
1	*Halictus viridatus* Lov.	*Pyrus malus*	*Pyrus malus*
1	*Halictus viridatus* Lov.	*Pyrus malus*	*Pyrus malus; Prunus*
1	*Halictus viridatus* Lov.	*Pyrus malus*	*Pyrus malus; Tulipa*
1	*Halictus viridatus* Lov.	*Pyrus malus*	*Pyrus malus; Taraxacum (15)*
2	*Halictus viridatus* Lov.	*Pyrus malus*	*Pyrus malus; Taraxacum*
1	*Halictus zonulus* Sm. (*craterus* Lov.)	*Lonicera tatarica*	*Lonicera; Caragana*
1	*Halictus zonulus* Sm. (*craterus* Lov.)	*Lonicera tatarica*	*Lonicera; Caragana; Spiraea; Tulipa*
1	*Halictus zonulus* Sm. (*craterus* Lov.)	*Lonicera tatarica*	*Lonicera*
1	*Bremus separatus* Cress.	*Pyrus malus*	*Pyrus malus; Syringa; Taraxacum*
1	*Bremus terricola*	*Pyrus malus*	*Pyrus malus (16)*
1	*Bremus terricola*	*Spiraea vanhouttei*	*Spiraea; Lonicera; Cornus*
1	*Colletes inaequalis*	*Pyrus malus*	*Pyrus malus*

(1) 1 grain Taraxacum only; (2) 2 grains Taraxacum only; (3) 3 grains Taraxacum only; (4) few Caragana; (5) also spores of Alternaria; (6) few grains only; (7) few Taraxacum only; (8) 1 grain Taraxacum only; (9) 1 grain Taraxacum only; (10) mostly Taraxacum; (11) 2 grains Taraxacum only; (12) 1 grain Taraxacum only; (13) 2 grains Taraxacum only; (14) heavy load of Pyrus; (15) 2 grains Taraxacum only; (16) 1 grain only.

The general results set forth in Table II can be studied best by reference to Table III.

TABLE III

SUMMARY OF PURE AND MIXED POLLEN LOADS CARRIED BY VARIOUS BEE SPECIES

Bee species	Pure loads		Mixed loads			
	No.	%	2 spp.	3 spp.	4 spp.	Total spp.
Apis mellifica	65	56.6	41	5	4	50
Andrena spp.	41	43.2	36	21	—	54
Halictus spp.	4	26.6	8	2	1	11
Bremus spp.	1	33.3	—	2	—	2

TABLE IV

THE HOST PLANTS OF *Andrena**

Insect	1	2	3	7	8	9	13	14	15	16	17	18	19	21	22	23	24	25	26	27	28	29	30	31	32	33	34	37	38	39	40	41	43	44
A. algida Sm. *(b)*													×																					
A. annae Ckll																	×		×															
A. bipunctata Prov.		×							×										×								×						
A. bradleyi Vier. *(g)*																																×		
A. canadensis D.T.				×								×															×						
A. carlini Ckll.																		×	×						×	×	×					×		
A. carolina Vier. *(e)*															×				×	×														
A. ceanothi Vier.											×							×	×						×	×							×	
A. crataegi Robt. *(f)*		×							×		×						×	×	×					×	×									
A. flavoclypeata Sm.									×									×	×															
A. forbesii Robt.																		×								×								
A. frigida Sm.								×										×								×								
A. grandior Ckll.																		×						×	×									
A. hirticincta Prov.				×								×															×							
A. kalmiae Atwood														×	×																			
A. lata Vier.																		×	×						×									
A. mandibularis Robt.														×				×	×	×														
A. mariae var. *concolor* Robt.					×			×									×	×	×						×	×								
A. milwaukeensis Graen.								×											×						×									
A. miranda Sm.		×			×									×				×	×						×	×								
A. multiplicata (a)																																		
A. nasoni Robt. *(c)*		×																×																
A. nebecula Sm. *(b)*																											×							
A. persimulata Vier.								×																								×		
A. placida Sm. *(d)*																		×	×															
A. regularis Mall.				×															×						×				×	×				
A. robertsonii D.T. *(b)*																							×											
A. rugosa Robt. *(b)*																		×																
A. thaspii Graen.					×						×				×						×			×	×		×	×						
A. vagans Ckll. *(b)*													×																					
A. vicina Sm.		×															×	×								×								
A. wheeleri Graen.						×		×														×			×									
A. wilkella (Kby.)	×		×		×				×			×	×			×		×			×	×			×			×		×	×	×		×

NOTE.—*(a), no host records; (b), one host record only; (c), two host records only; (d), also found on Acer; (e), also found on Claytonia and Dentaria; (f), also found on Spiraea; (g), also found on Ribes.*

**The hosts are given a number corresponding to the accompanying list, and a positive record is marked* ×.

TABLE V

HOST PLANTS OF *Halictus*

Insect	1	2	3	5	6	7	8	9	12	13	15	16	17	18	19	20	21	23	24	25	26	29	30	31	32	33	34	35	36	37	39	40	41	42	44
H. arcuatus Robt.										×		×		×						×	×		×	×	×		×								
H. athabascensis Sandh. *(C.r.)*														×							×										×		×	
H. confusus Robt. *(a)*																																			
H. craterus Lov.	×																				×														
H. coriaceus Sm.			×				×				×		×								×	×			×		×								×
H. cressoni Robt.		×	×																	×	×				×		×					×			×
H. foxii Robt. *(s)*				×			×			×			×							×	×	×						×							
H. leucozonius (Shrank) *(r)*	×				×	×		×				×	×	×		×			×	×	×					×		×				×	×		×
H. lineatus Craw. *(a)*																																			
H. macoupinensis Robt.							×							×											×							×			
H. nymphearum Robt.																		×									×					×			
H. pectoralis Sm.	×					×	×		×	×			×	×		×		×						×	×		×		×	×					
H. pilosus Sm. *(r.a)*		×					×						×							×	×						×					×			
H. provancheri D.T. *(c)*							×							×	×			×		×	×						×								
H. quebecensis Craw.																	×			×	×														
H. rubicundus (Christ.)	×						×			×	×							×			×				×	×	×				×		×		
H. rufitarsus Zett.		×												×							×														
H. sparsus Robt.		×																	×	×					×		×				×				
H. viridatus Lov.				×		×	×		×				×	×				×			×	×				×	×				×		×		
H. zonulus Sm. *(s.v.)*	×						×		×	×				×		×		×			×			×			×	×	×			×			

NOTE.—*(a), no host records; (c), also taken on Cerastium; (c.r), also taken on Cornus; (r), also taken on Rudbekia; (r.a), also taken on Raphanus; (s), also taken on Spiraea; (s.v.), also taken on Senecio and Viburnum.*

Discussion of Results

An examination of Tables II and III does not alter the conclusion arrived at as a result of former studies (1, 2). *Halictus* and *Bremus* species, however, were taken in such small numbers that the results have no statistical value. *Andrena* spp. as a group, show a lower degree of constancy than *Apis mellifica* L., and less than that exhibited by *Halictus* in former studies, to which reference has been made.

Availability of any particular bloom again appears to be the main factor in determining the degree of constancy exhibited. It is only to be expected that where any particular plant species predominates the bees visiting the blossoms of that particular plant would show a high percentage of pure loads. It must be admitted, however, that these studies do not indicate as high a degree of flower constancy for the hive bee as has been claimed by some workers.

From an examination of Tables IV and V, in which the host records of the bees captured are summarized, it will be seen that species most commonly occurring on the apple are those that show the widest range of food plants. All species of both genera commonly occurring in the region appear among the captures from this host. The fact that a species is recorded from only a few hosts or from a single host does not necessarily indicate oligotrophy, since such species are those that appear to be rare in the region studied, and hence the probability of their being taken on any particular host is reduced. Doubtless, a more intensive survey and particularly a closer study of the early flora would produce results of interest.

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ON THE PREVALENCE OF PATHOGENIC FORMS OF *HELMINTHOSPORIUM SATIVUM* AND *FUSARIUM CULMORUM* IN THE SOIL OF WHEAT FIELDS AND ITS RELATION TO THE ROOT ROT PROBLEM[1]

By G. B. Sanford[2] and W. C. Broadfoot[3]

Abstract

A total of 227 isolates of *Helminthosporium sativum* and 286 of *Fusarium* sp. (*culmorum* type) were obtained from the diseased crown tissue of wheat stubble in five fields located in the black soil belt of central Alberta, and an attempt was made to determine their relative virulence on wheat seedlings and on mature plants. The experiment was carried out under greenhouse conditions, with a range of soil temperature. Sterilized, artificially infested soil in open pot culture was used. The results indicated that the *Helminthosporium* isolates were as a rule moderately to weakly pathogenic, and that most of the *Fusarium* isolates were only weakly pathogenic to wheat plants in the seedling stage. Some isolates of each pathogen exhibited extreme virulence, but judging from the results on seedling plants, virulent strains were rather rare in the fields studied. On mature plants both fungi showed about equal degrees of virulence, which was on the whole weak, and the results were not considered significant for the purpose of the study. More isolates of the greater degrees of virulence were obtained from certain fields than from others. In view of the great susceptibility of seedling plants in sterilized re-infested soil and the variable results, presumably caused by association effects of contaminants of the soil in open pot culture, it was concluded that the object of the study could not be attained by means of data based on the seedling stage, or by the technique employed. The possibility of significant results being secured in sterilized re-infested soil, protected from contamination, and based only on mature plants, is discussed in relation to the root rot problem.

Introduction

It is well known that there is much variability in virulence among isolates of either *Helminthosporium sativum* P.K. and B., or *Fusarium culmorum* Smith, both of which are root rotting pathogens of cereals, and that the phenomenon is a type of physiologic specialization common among many fungi.

Stakman (15), in discussing "Racial specialization in plant disease fungi", dealt with its significance in breeding for resistance, and reviewed the contributions of many workers on this subject. Stevens (17) and Christensen (5) and others have given evidence of the diversity of *H. sativum*, and Brown (4) and others, of the diversity in the genus *Fusarium*. Craigie (7) showed how physiologic forms of *Puccinia graminis tritici* may originate by hybridization on *Berberis vulgaris*. Hanna (9), Stakman *et al.* (16) and Christensen (6) have demonstrated that many physiologic forms of *Ustilago zeae*, which differ in virulence, exist and that they may originate by hybridization and mutation. The interesting treatise of Brierley (1) deals theoretically with the origin of racial diversity among fungi and bacteria. Dickinson

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(8) concluded that saltant strains of *F. fructigenum* are the result of mutations, while Hansen and Smith (10), from work on *Botrytis cinerea* Pers., maintain that the variable forms of Fungi Imperfecti may owe their instability, not to mutation, but to nuclear heterogeniety (heterocaryosis) induced by anastamosis of hyphae and unequal cell divisions.

By whatever method diverse forms may occur in *H. sativum* and *F. culmorum*, the fact that they are numerous in nature probably affects greatly the problem of synthesizing varieties resistant to the root diseases of cereals which they cause. The work of Broadfoot (3) indicated that both fungi are extremely common in the crown tissue of wheat in average field culture, and that a number of crop sequences appeared to have no perceptible effect on their relative prevalence as suggested by isolations. But the immediate problem in a plant breeding program appears to be concerned, not so much with the prevalence of these organisms, as with the degree of virulence most common in the average field. Apparently no information is available as to whether certain crops make any perceptible difference in the ratio of the more virulent forms to those less virulent. If virulent forms are relatively scarce in our soils, and moderate pathogenicity the common thing, it would appear that it would be advisable to obtain first the necessary resistance to withstand the moderate degree of virulence common under field conditions. Particularly is this true when our wheat varieties do not possess marked resistance. Therefore, the object of this study was to obtain a general picture of the degree of virulence which exists among isolates* of *H. sativum* and *F. culmorum* in wheat fields in Alberta.

Materials and Methods

Choice of fields. In accordance with the objects of this study, each year from 1928 to 1932 inclusive, one field of wheat, suffering from *Helminthosporium* root rot and *Fusarium* root rot, was located at some point in the black soil belt of central Alberta. The soil reaction of these fields, according to the report of Wyatt and Newton (19), would be approximately pH 6.2. Fields suffering from typical *Ophiobolus* root rot (take-all) were, as far as possible, avoided, and isolations were not made from plants known to be suffering from this root rot. However, the writers' opinion, which is supported by the work of Robertson (12), is that plants may not indicate the typical take-all symptoms, even though the major injury is caused by *Ophiobolus graminis* and the tissue yields either or both *H. sativum* and *F. culmorum*. Stubble was pulled from five different fields at harvest time. The location of each field is indicated in Table I. The samples of stubble from which isolations were made were taken at random from an area of about four acres. About 80 separate liberal samples of the stubble were pulled from as many equidistant points in each field and numbered.

Obtaining isolates. From each composite sample of stubble the crown and the main tiller base of several plants showing signs of crown infection were

**Used in this paper as a noun in the sense of 'isolations' and without regard to possible racial differences.*

taken. This portion was surface disinfected for two minutes in mercuric chloride solution (1:1000) and incubated on solid potato sucrose agar. Subsequently, pure cultures of *H. sativum* and *F. culmorum** were obtained, from which single spore isolates were chosen for the pathogenicity test to be made. The total number of isolates of *H. sativum* and *F. culmorum* thus obtained was 513, made up of 227 of the former and 286 of the latter. As these were tested at various temperatures, both in the seedling and maturity series, the total number of tests of *F. culmorum* in the seedling stage was 668, while for the mature series it was 291. The corresponding figures for *H. sativum* are 487 and 133.

Pathogenicity tests. These were made in open pot culture in sterilized artificially re-infested soil, under greenhouse conditions during the late fall, winter and early spring months. The reduced daylight during this period was supplemented by electric illumination. In each case the isolations were tested for damage to the seedling stage, and in all but two cases for that to the mature plants. A range of soil temperature, the lowest being 13° C. and the highest 21° C., was employed. Each isolate chosen for test was increased on ground sterilized oat hulls and aged for 30 days, after which 10 gm. of it was scattered at seed level in each six-inch pot, and covered. For the seedling series, 15 grains of Marquis wheat were planted in each of the four replicate pots used to test each isolate, and for the mature series, seven grains. The number of control pots in each temperature series was approximately one-tenth of the test pots involved. The temperature used, and the number of isolates of each fungus tested at each temperature, in both series mentioned, are shown in Table I.

Estimating virulence. The degree of injury of each plant was estimated numerically, taking into consideration the percentage of plants which did not emerge, the condition of the crown, the mesocotyl, the primary root system, and the height of the plant. This rating was translated into percentage infection, and the isolates arranged in virulence classes, as given in Table I. The condition of the coleoptile was disregarded as, in the writers' opinion, it is early subject to discoloration by ordinary saprophytes, even in the soil of control pots.

Results

The summarized data, which are given in Table I, will for convenience be elaborated for each field. Some of the data are presented in chart form in Fig. 1.

Seedling Series, F. culmorum

Taking first the seedling series of the Camrose field, all of the 63 isolates tested at 16° C. fell into the virulence class below 10%; 93.8% of those tested at 18° C., and 93.1% of those tested at 17° C. fell into the same class. None exceeded the 20% class.

**Wherever F. culmorum is mentioned subsequently in this paper, Fusarium of the culmorum type is intended.*

TABLE I

THE VIRULENCE OF RANDOM ISOLATES OF *Fusarium* SP* AND *Helminthosporium sativum* FROM WHEAT STUBBLE OF FIVE DIFFERENT FIELDS, EXPRESSED ON (I) THE SEEDLING STAGE, AND (II) MATURE WHEAT PLANTS. THE PERCENTAGE OF ISOLATES IN THE VARIOUS VIRULENCE CLASSES IN EACH TEST ARE INDICATED FOR EACH PATHOGEN

Series	Fields	Temp., °C.		*Fusarium* sp.										No. Isolates	*H. sativum*										No. Isolates
				Virulence classes, %											Virulence classes, %										
		Air	Soil	0+	10+	20+	30+	40+	50+	60+	70+	80+	90+		0+	10+	20+	30+	40+	50+	60+	70+	80+	90+	
I. Seedling	A		18	93.8	6.2									64	81.8	18.2									11
			16	100										63	100										11
			17	93.1	6.9									58	90.0	10.0									10
	B	21	17	97.0				3.0						33	25.0	30.0	17.5	15.0	5.0	2.5	5.0				40
	C	19	17	55.2	30.6	4.2	2.0	2.0	2.0	2.0				49	2.6	15.8	15.8	47.4	7.9	7.9	2.6				38
		23	20	41.3	58.7									46	2.6	5.3	28.9	34.2	23.7	5.3					38
	D	24	21	12.3	46.5	30.1	1.4	1.4	1.4		1.4		5.5	73		1.6	4.8	11.1	14.3	20.6	25.4	17.5	4.7		63
		16	13	19.4	62.5	6.9	2.8				1.4	2.8	4.2	72	3.1	20.3	31.3	15.6	12.5	17.2					64
		21	18	9.7	65.4	13.9	4.0	1.4	1.4	1.4	1.4	1.4		72	1.6	4.7	18.8	15.6	12.5	14.0	14.0	9.4	4.7	4.7	64
		22	19	25.0	58.8	8.8	1.5	2.9		1.5		1.5		68	3.1	7.8	4.6	25.0	31.3	6.3	9.4	7.8	4.7		64
	E	19	17	53.7	28.3	9.0	1.5	4.5		3.0				67	24.3	25.7	14.9	18.9	13.5	2.7					74
Summary				51.3	35.2	7.7	1.4	1.4	0.4	0.8	0.4	0.4	1.0		13.2	15.2	15.0	19.3	14.2	9.2	7.0	4.5	1.8	0.6	
II. Mature	A		18	10.9	35.9	40.6	10.9	1.7						64	54.5	36.4		9.1							11
			16	15.9	41.3	26.9	15.9							63	36.4	63.6									11
			17	22.4	55.2	20.7	1.7							58	45.5	54.5									11
	B	21	17	33.3	54.6	9.1				3.0				33	75.0	25.0									40
	D	18	15	20.6	67.1	12.3								73	1.7	31.6	33.3	25.0	6.7	1.7					60
Summary				19.2	50.9	23.0	6.3	0.3		0.3					34.6	34.6	15.0	12.0	3.0	0.8					

*Of the culmorum type. †A, Camrose; B, Bittern Lake; C, Westlock; D, Fort Saskatchewan; E, Edmonton.

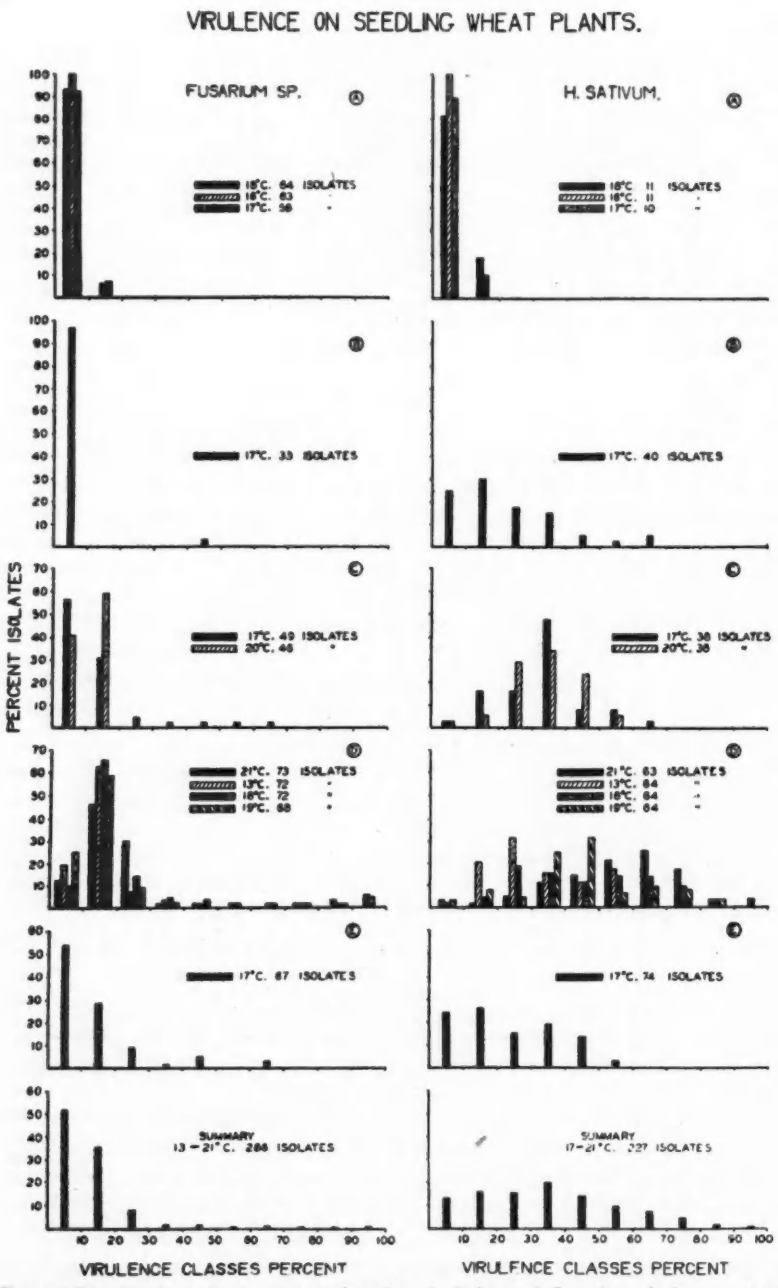

FIG. 1. *The prevalence in percentage of pathogenic isolates of Fusarium (culmorum type) and Helminthosporium sativum, as obtained at random from the wheat stubble of five fields. The pathogenicity was read on seedling wheat plants. A, B, C, D, and E indicate the location of each field (see Table I).*

Of the 33 isolates from the Bittern Lake field tested at 17° C., 97% were in the class below 10%, and the balance were in the class from 40 to 49%.

Of the 49 isolates from the Westlock field, tested at 17° C., slightly over 55% of them fell into the lowest virulence class, 30.6% of them into the next higher class, 4.2% into the next class, and 2% into each of the classes 30+, 40+, 50+ and 60+. In the test made at 20° C., 41.3% were in the lowest class, and the remainder in the next class.

Fort Saskatchewan isolates provided the most interesting results, because a much larger proportion of them fell into higher virulence classes than was the case with those from other fields. For example, we find in some instances approximately 1.4% of the isolates in the class above 60%, and two instances, namely 5.5% and 4.2% of the 72 to 73 isolates in the class above 90%. Apparently the differences in soil temperature did not affect greatly the distribution of the isolates within the virulence classes, at least as much as one might expect in view of previous work. Although the writers are unable to offer an explanation for the greater virulence shown by the isolates from this field, it may be mentioned that the wheat stubble, from which these isolates were obtained, followed a crop of barley, whereas those from other fields were obtained from the stubble of the third consecutive crop of wheat.

Results from the 67 isolates from the Edmonton field are on the whole comparable to those obtained from the Westlock field, 82% of them falling into the virulence class below 20%. None were as virulent as several isolates from the Fort Saskatchewan field.

Thus, considering all isolates from all five fields, 51.3% fell into the lowest class, 35.2% into the next higher class, 7.7% into the 20+ class, and 1.4% into the 30+, and 40+ classes, respectively, and less than 1% into those between 40+ and 90+ virulence, and only 1% into the highest class. Perhaps most obvious is the rarity (except in the peculiar case of the Fort Saskatchewan field) of virulent strains from the fields, the great bulk of the isolates being only slightly pathogenic to non-pathogenic on wheat in the very susceptible seedling stage.

Mature Series, F. culmorum

There is a striking contrast between the virulence of *F. culmorum* as indicated at the mature stage, and that at the seedling stage. A possible reason for this will be given later in the discussion of results. In most instances a smaller percentage of the isolates fell into the lowest virulence class and, in general, more into the next higher class, than was the case in the seedling series. Practically all of them fell into virulence classes below 40%. From 36 to 67% of the isolates from the three fields tested at various temperatures fell into the 10 to 19 virulence class, with a larger proportion of them indicating approximately 12%. Of the 33 isolates from the Bittern Lake field, and the 73 isolates from the Fort Saskatchewan field, 9.1 and 12.3% were in the 20 to 29% class, while of those from the Camrose field (isolations from Westlock and Edmonton fields were not tested in mature series) 20.7 to 40.6% were in this class.

Although in the three tests made at 16, 17 and 18° C., the same isolates were used, there was considerable variation in results. While it is possible that some of this irregularity may be accounted for by the size of class used, there were other factors, the importance of which will be mentioned later.

TABLE II

TYPICAL EXAMPLES OF THE VARIABILITY IN VIRULENCE DURING FOUR TESTS ON SEEDLING WHEAT PLANTS OF THE SAME ISOLATES OF *Fusarium* SP.* AND *Helminthosporium sativum*

Isolates	1st test		2nd test		3rd test		4th test		Average	
	Plants**	R†	Plants	R	Plants	R	Plants	R	Plants	R
Fusarium sp.										
P–10	0.7	96	3.5	82	4.7	69	10.2	31	4.7	69
13	0.7	92	1.2	92	1.7	88	2.2	85	1.4	90
R– 2	13.5	13	0.5	93	14.0	20	12.5	17	10.1	37
7	4.2	76	6.5	83	14.0	16	11.7	23	9.1	49
19	0.5	96	1.7	91	11.0	30	13.2	11	6.6	57
H. sativum										
14–13	7.0	69	8.5	56	5.2	97	12.2	34	8.2	64
15– 1	7.5	66	11.2	50	7.0	94	10.5	39	9.0	62
3	3.0	86	10.2	58	8.0	59	9.0	46	7.5	62
16–17	4.5	78	9.7	50	7.0	67	7.2	58	7.1	63
17–11	2.7	87	8.7	59	6.5	71	3.5	80	5.3	74
Controls	13.7		13.7		14.0		13.6		13.8	
Air temp., °C.	24		16		21		22			
Soil temp., °C.	21		13		18		19			

*Of the culmorum type. **Average number of plants per pot from 15 grains. †Infection rating, percentage.

Examples of this type are given in Table II, where it will be observed that the infection rating for the same isolates varied greatly in the four separate tests made. For instance, *F. culmorum*, Culture *P*-10, was quite pathogenic in the first, second and third tests, but not in the fourth one; Culture *R*-2 was pathogenic in the second test, but not in the others; Cultures *R*-7 and *R*-19 were pathogenic in Tests 1 and 2, but not in the others; whereas Culture *P*-13 was pathogenic in all four experiments. Similarly, with *H. sativum*, although the variation was not so great, Culture 17-11 was quite pathogenic in all experiments, but Cultures 14-13 and 15-1 were quite pathogenic in Tests 1 and 3, and not in 2 and 4, whereas Cultures 15-3 and 16-17 were quite pathogenic in Test 1, but not as pathogenic in the other three trials. This variability is also clearly indicated by the number of surviving plants. Undoubtedly, such results cannot be explained on the basis of the slightly different soil temperatures of the four tests. Similar variability was evident for many other cultures during the five years of study.

However, the data given in Table I suggest that in the mature series practically all the isolates fell into the virulence classes below 30%, although a number of them were in higher classes in the seedling stage. It also indicates, as

far as can be determined by the technique used, that the degree of virulence of *F. culmorum*, as it exists in the soil of wheat fields, is on the whole slight. Apparently very virulent strains are not prevalent, or they were not indicated by the method.

Seedling Series, H. sativum

Only 11 isolates of *H. sativum* were obtained from the Camrose field, the issue from the crowns being almost wholly species of *Fusarium*. However, all of these, subjected to three different tests at temperatures 16, 17 and 18° C., respectively, exhibited only slight virulence, and none exceeded 10%. In one case all were in the lowest class, in another, 90%, in a third, approximately 82%.

Of the 40 isolates from the Bittern Lake field, tested at 17° C., 25% were in the class below 10%, 30% in the 10+ class, 17.5%, 15% and 5% in classes 20+, 30+ and 40+, respectively, and of the remainder, 2.5 and 5% in the 50+ and 60+ classes.

The results from the 38 isolates from the Westlock field, tested at 17° C., were on the whole fairly comparable with those from the 40 isolates obtained from the Bittern Lake field, except that there was a tendency for greater virulence, as indicated by the fact that only 2.6% of them fell into the lowest class, 47.4% into the 30+ class, and 15.8% into each of the classes between. None exceeded the 60+ class. Similarly, at 20° C. the larger proportion of them, namely 28.9, 34.2 and 23.7% were in the 20+, 30+ and 40+ classes, respectively, while of the remainder 2.6, 5.3 and 5.3% were in the 0+, 10+ and 50+ classes. It will be observed that at 20° C. there was a greater shift toward the higher classes than at 17° C. This tendency is also apparent with the 64 isolates from the Fort Saskatchewan field, where the results at 18, 19 and 21° C. may be compared to those from the test made at 13° C. However, it is obvious that the difference is not as great as might be expected, in view of the prevailing idea on the differential effects of temperature. Of particular interest is the tendency for a greater virulence of the isolates from the Fort Saskatchewan field than of those from the other four fields, and in this respect comparable to the results from the *Fusarium* isolates from the same stubble.

Considering the results from all five fields, it is clear that a much larger proportion of the isolates of *H. sativum*, as obtained at random from the field stubble, were much more pathogenic to wheat in the seedling stage than were the *F. culmorum* isolates. Approximately 85% of the *F. culmorum* isolates indicated virulence below 20%, while about 30% of the *H. sativum* isolates fell into this class, the others into classes up to 90%, and the major portion of them into classes between 20 and 50%.

Mature Series, H. sativum

The virulence of the 11 isolates from the Camrose field, tested at 16, 17 and 18° C., indicated little damage over that occurring in the seedling series. Seventy five per cent of the 40 isolates from the Bittern Lake field, tested

at 17° C., fell into the lowest class, and the remainder into the 10 to 19% class, thus indicating much less damage than occurred to plants in the seedling stage. The 60 isolates from the Fort Saskatchewan field, tested at 15° C., also indicated a lower virulence than they produced on the seedling stage at 13° C.; 90% of them being in the classes from 10 to 39%, and of the balance 6.7% were in the 40 to 50% class, and 1.7 in the 50+ and lowest classes, respectively.

Discussion

In general, the data presented indicate that moderate to weak virulence was the rule with the *Helminthosporium* isolates in the seedling series, and that the *Fusarium* isolates were, on the whole, only weakly pathogenic. A few isolates of both fungi exhibited marked virulence and, according to the results, these were more common in certain fields than in others but, in any case, their occurrence was relatively rare. On mature plants the isolates of both fungi showed about equal degrees of pathogenicity, which was weak or apparently absent, particularly in the case of the *Fusarium* isolates. If the foregoing results can be accepted as reliable, the study was successful in demonstrating that moderate to weak pathogenicity is the rule in the average field, and that very virulent strains are relatively rare, and consequently the plant breeding problem is, for the moment, simplified in proportion.

Thus comment appears to centre on whether the method used was suitable for the purpose indicated. Admittedly, the general technique employed in testing the isolates in open pot culture in sterilized soil was that which has been used by many workers in the past, and the one on which most of the published results on the root rotting pathogens *H. sativum*, *F. culmorum* and *O. graminis* have been based. As mentioned earlier, there were four pot cultures for testing each isolate each time at the various temperatures. Thus, in testing the *Fusarium* isolates there were 2672 test pots involved in the seedling series, and 1164 pots in the mature series, and for the *Helminthosporium* isolates the corresponding numbers were 1948 and 532. However, in spite of the liberal replications, the great variability which occurred among separate tests, among replicate pots, and among the plants within a given pot, and the fact that the results from the mature series were roughly opposite to those obtained on the seedling plants, throws much doubt on the significance of the data or its value for the purpose sought. As a matter of fact, in one test (seedling series) an isolate might indicate weak pathogenicity, and in another, under apparently similar conditions, be definitely virulent, and *vice versa* (Table II).

Possibly some of the variability indicated might be accounted for by genetic changes in the isolates, but, with open pot culture methods, using sterilized soil, the results obtained could probably not have been much different. The pathogen in sterilized soil would at first exert its full effect on the very susceptible seedling plants, but in a short time contaminants (fungi and bacteria) or combinations of these, which may be antagonistic to the isolates being tested, quickly occupy the sterilized soil to the detriment of the pathogen

under test. The writers (13) have demonstrated this in connection with *O. graminis*, and have found by experiment that it also applies to *H. sativum* and *F. culmorum*. Henry (11) has also demonstrated the phenomenon as it concerns the last mentioned pathogens. Further, Broadfoot (2) has shown how quickly the virulence of *O. graminis* may be vitiated in sterilized soil in open pot culture. For example, its virulence on wheat seedlings dropped from 65 to 48, 41, 20, 25, and 13%, when planted 10, 20, 30, 40 and 50 days, respectively, after the inoculum was added to the originally sterilized soil. It appeared practically impotent at the end of 120 days. Thus, in view of the differences mentioned, it is doubtful whether the data obtained in the mature series of this study are significant. In regard to those obtained from the seedling series, it is necessary to consider the great susceptibility of these plants, especially in sterilized soil, where even weak pathogens may be effective, and often sufficiently so to prevent the demonstration of definite pathogenic differences among the isolates.

To avoid the difficulties mentioned, it would seem necessary that the test be made in sterilized re-infested soil protected from outside contamination, and that results be based only on the reaction of mature plants. The inoculum of the isolate would then be added during the post-seedling stage. The question is also raised whether plants, after the post-seedling stage, become more or less susceptible toward maturity and, as well, the relation of resistance to vigor, as affected by light intensity, moisture, temperature, nutrients, and the pentosan content of the plants, all of which are not well understood at present. Tyner (18) found that wheat plants, grown under normal illumination, had a definitely higher pentosan content per unit mass than when the light was subnormal, and that increased pentosan content appeared to be associated with increased vigor and greater resistance to root rot caused by *O. graminis*.

Thus, with sufficient information, standard experimental conditions could be evolved and used in an attempt not only to produce a general picture of the virulence of root rotting pathogens in the average wheat field, but possibly to determine the degree of natural resistance which varieties and hybrids may possess. Obviously the performance in the field of a variety which may indicate resistance under laboratory conditions must, in the final analysis, be ascertained.

Testing for natural resistance of varieties in the field in infested soil would theoretically give positive results, provided a sufficient degree of resistance existed. However, in view of the possible confusing effect of diverse forms of each pathogen, and the well recognized effect of extremely variable environmental factors in the field, and the apparently indefinite resistance which our present varieties possess, the field method would seem to have very great limitations. At least, results at this laboratory (14) from testing in the field over 100 varieties and hybrids for resistance to these pathogens during the past six years would seem to support this contention. Moreover, in western Canada, it is in the damage to the post-seedling stage of wheat

plants that the main problem lies. In the writers' opinion, seedling blight, although important in certain seasons and cases would easily occupy a secondary position. Serious root rot damage by these fungi does not begin to manifest itself until late in June, unless under drought conditions, when it is too late for natural compensating factors to operate effectively.

Finally, the urgent need for better information must be admitted, for it is doubtful whether we have an adequate conception of the root rot problem as it is affected by the prevalence of pathogenic forms in the field, or a definite indication of the natural resistance which our varieties of cereals may or may not possess.

Acknowledgments

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BACTERIOLOGICAL STUDIES ON THE RED DISCOLORATION OF SALTED HIDES[1]

By A. G. Lochhead[2]

Abstract

A study was made of organisms concerned with the red discoloration of salted hides, also termed "red heat", which defect may occasion loss in the leather industry through spotting and weakening of the fibre. Red halophilic sarcinae were isolated from Argentine hide. From Canadian hides showing red discoloration, two species of pleomorphic rods were isolated as active agents. One of these, occurring on salted cowhides, was found to be similar to *Serratia salinaria* (Harrison and Kennedy) Bergey *et al.*, a source of reddening of cured codfish in eastern Canada. The other organism causing discoloration, isolated from buffalo hide, was regarded as a new species and designated *Serratia cutirubra* n.sp. Both of these halophilic organisms, owing to their proteolytic action, are considered capable of greater damage to hides than the red sarcinal types which are non-liquefying, and which may also be present on Canadian hides. Non-chromogenic halophilic bacteria were also isolated from discolored hides. These develop at a lower salt concentration range than the red organisms and are probably less active in causing injury to fibre in well salted hides.

Introduction

In September 1932 the attention of the writer was called by Dr. W. E. Graham of the National Research Council to the question of the reddish discoloration frequently appearing on salted hides. This question had been raised by the Associate Committee on Leather of the National Research Council and was under consideration in its general aspects by Dr. Graham. This discoloration, commonly referred to in the leather trade as "red heat", becomes evident on the flesh side of the hide during storage and represents a defect which may occasion considerable loss to the industry through spotting and weakening of the fibre.

The appearance of the discoloration suggested a possible analogy to somewhat similar defects occurring on other salted products, notably codfish, caused by salt tolerant bacteria, types of which might be expected to be active on salted skins. Samples of discolored hides were placed at the disposal of the writer by Dr. Graham, and the present report summarizes the work on the isolation and study of the causal and associated organisms.

Historical

A number of studies have already been reported dealing with the relation of micro-organisms to the appearance of red discoloration on various salted animal products, particularly fish, though occasional references to work with other products, such as sausage casings and hides, may be found. The various organisms indicated as causal agents represent a variety of types including micrococci, sarcinae, spore-forming and non spore-forming rods, spirochetes, algae and yeasts. While in many cases the organisms concerned were prob-

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ably the same, an accurate comparison is difficult or impossible owing to the incompleteness of many of the descriptions. Furthermore, in some of the earlier work especially, there are omitted many essential details, such as the media employed, the effect of salt concentration on the organism, and in some cases, the critical experiment of producing the reddening with the organism said to be the cause.

A detailed review of the work reported dealing with the reddening of fish would appear out of place. For this the reader is referred to such publications as those of Kellerman (9), Harrison and Kennedy (8), Cloake (5), and Hanzawa and Takeda (7). It is of interest, however, that there is almost complete unanimity in ascribing the source of infection to the various salts used for curing. The probability of similar sources of organisms causing discoloration of hides suggests a close relation of the reddening of these two salted products.

The first reported work on the red discoloration of salted hides appears to be that of Becker (2) who cultivated from reddened areas a strictly aerobic micrococcus, 1.1–1.5 μ in diameter, isolating in addition a species of torula, with cells approximately 6–7.5 μ in diameter. Since neither the micrococcus nor the torula showed any power of gelatin liquefaction, the author regarded the discoloration as harmless. Discoloration with more deleterious effects has been reported anonymously (1). Red spots noted in raw salted calfskins, which were found to be coextensive with damaged spots in the grain after finishing, were stated to be due to aerobic, proteolytic bacteria. On the other hand, in a report issued by "Frigorifico", according to Stather and Liebscher (20) the red discoloration on the flesh side of raw hides is caused by strongly aerobic, halophilic bacteria or molds which develop superficially, causing no material damage.

In 1929 Stather and Liebscher (20) reported the first of a series of investigations on the pink to brick red discoloration occurring on the flesh side of raw hides which they consider due to micro-organisms. The discoloration is regarded as a definite defect, resulting in a weakening of the hides, histological and chemical analyses indicating a definite loss of hide substance. Later the same authors (21), reporting their bacteriological studies, describe seven organisms isolated from reddened areas which they classify as *Sarcina lutea*, *Sarcina aurantiaca*, *Micrococcus tetragenus*, *Micrococcus roseus*, *Bacillus subtilis*, and two organisms regarded as *Proteus* and *Actinomyces* types respectively. Of these the last two organisms together with *S. aurantiaca* and *M. roseus* were chromogenic in various shades of red on artificial media. Of these, two were suppressed by a concentration of 8%, the others by 16% sodium chloride which raises doubt whether such types, widely distributed in dirt and dust, develop sufficiently to cause discoloration on the surface of salted hides. No examination for strict halophiles appears to have been made.

Investigating "red heat" of salted hides, Lloyd, Marriott and Robertson (12) paid special attention to halophilic organisms occurring in curing salts. With media of 16 to 30% salt concentration, strains of red and yellow sarcinae were isolated. Both types were obligate aerobes, strongly halophilic, grew

best at 37° C. and at 100% humidity. Gelatin was liquefied by the yellow, though not by the red organisms, consequently the latter were considered less likely to damage the hide fibres. The authors point out that on salted hides a mixed flora of halophiles and other organisms exists and suggest that the actual damage may be due to associative action.

Referring to the above work, Stather (19) suggests that the halophilic organisms causing "red heat" are not essentially different from the types isolated by himself and Liebscher from "red discoloration". The organisms from the latter were trained to survive on 20% salt, while cultures of halophiles of the English workers were said to have been trained to withstand low concentrations. The question of the relative ability of the organisms to produce the effect on salted hides was apparently not considered. Robertson (17), in considering whether halophilic organisms alone are responsible for red growths on hides, or whether ordinary red chromogens of dust and dirt also play a part, reports an investigation of the capacity for growth and survival at different salt concentrations of the two types. The red halophiles were found to flourish best at high salt concentrations, failing to develop with concentrations below 6 to 10%. On the other hand the organisms of dirt and putrefaction, including those described by Stather and Liebscher (21), failed to multiply with more than 8% salt, though some survived for various periods in the higher concentrations. Robertson believes that marine curing salts are the source of the halophiles causing discoloration, though in a later paper (18) she indicates the possibility that chromogenic dust and dirt organisms may play a minor part. A study of the effect of various antiseptics showed boric acid and borax to be useless for inhibiting halophilic growth, while sodium carbonate and sodium bisulphite produced ill effects on the hide fibre. Naphthalene, while inhibiting the bacteria for a few weeks without damaging the hide, lost its effect after this period, presumably owing to volatilization. Sodium fluoride, 0.5%, added to the curing salt, was stated to be the most satisfactory antiseptic tried.

A red discoloration of salted hides due to an obligate halophilic coccus is reported by Blankow (3). In line with the findings of Lloyd and coworkers are his observations that marine curing salts are the source of infection. Further evidence that hide curing salts are the source of infection is given by Stuart, Frey and James (22). In 34 out of 35 samples of crude solar salts and in 25 out of 29 open pan evaporated salts red chromogens, capable of causing reddening on calfskin, were found. On the other hand all kiln dried solar salts, all vacuum pan evaporated salts and all mined or rock salts examined were found to be free of such organisms.

Experimental

Methods

For the isolation of the halophilic organisms studied, three special media were used, employed with varying concentrations of salt.

Medium A:—beef extract, 3 gm.; yeast extract, 3 gm.; peptone, 10 gm.; soluble starch, 10 gm.; agar, 15 gm.; salt and distilled water to make 1000 cc.

Medium B:—½ lb. minced codfish steamed with one litre water for one hour and strained through several layers of cheese cloth; peptone, 1.0 gm.; glycerine, 5 gm.; agar, 15 gm.; salt and water to make 1000 cc.

Medium C:—to prepare 1 litre, 500 cc. fresh skimmilk, 15 gm. agar in 200 cc. water and salt, depending on the sodium chloride concentration desired, are sterilized separately. The hot ingredients are mixed in one flask, by adding the milk to the salt and this mixture in turn to the agar. Additional hot water is added gradually with shaking to make a final volume of 1000 cc. When the salt is dissolved the hot medium is poured into Petri dishes (or tubes for slanting) and when hard is ready for use.

The more detailed cultural and physiological tests on the organisms were carried out on various substrates at a favorable salt concentration, the effect of sodium chloride having been determined for each organism, using the most suitable basic medium. Observations were continued for three to four weeks and longer in the case of gelatin liquefaction. This latter determination presents some difficulty owing to the tendency of salt to prevent solidification. By using 25% gelatin, however, a medium containing 20% sodium chloride was prepared, which though not as firm as ordinary gelatin media, was satisfactory for determining liquefaction when used as slants with surface inoculation by the loop method.

For microscopical examination and slide preparation the organisms were suspended in a salt solution the strength of which corresponded approximately to that of the medium. In the case of the non-chromogens and the red sarcinae little difficulty was encountered by varying the salt concentration of the suspension, the organisms being fairly resistant to plasmoptysis. With the red pleomorphic rods much care to prevent rupture of the cells was required, the staining being correspondingly more difficult. The most generally satisfactory method was to add the culture to a large drop of 20% sodium chloride in a Petri dish, with little stirring. A loopful of this is transferred to a clean slide, gently spread and allowed to dry without heating. Immediately the smear is dry it is flooded with absolute methyl alcohol for two to three minutes, renewing if necessary. The excess alcohol is poured off and the stain added directly, without previous washing. For single stains 1% aqueous basic fuchsin was found to be most generally satisfactory, staining one to three minutes. Giemsa and aniline carbol gentian violet were also found useful. For flagella staining, Muir's modification of Pittfield's method was used. Instead of the absolute methyl alcohol used for the preliminary fixing, the acetic-alcohol fixative used by Browne (4) was occasionally found to be more suitable (one part glacial acetic and one part absolute alcohol).

For hide inoculation tests, fresh calfskin was used, clipped, cut into pieces 2 in. square, washed well with water and placed in Petri dishes. Sterile sodium chloride was added in excess. After inoculation water was added from time to time if necessary to prevent desiccation.

Isolation of Organisms from Hides

Three types of green salted hides showing discoloration were studied, Argentine steer hide, Canadian cowhide and Canadian buffalo hide.

Examination of discolored areas, dark pink in shade, on the Argentine hide, showed the organisms to be almost entirely micrococci, variously grouped in pairs, fours, or in irregular clusters with indication of sarcinal arrangement. Medium *A*, with 15 to 25% salt, proved the most suitable substrate for isolation, growth of reddish colonies becoming first apparent after four to five days' incubation at 37° C. with the higher salt concentration, and after two weeks on the 15% salt plates. Non-chromogenic, halophilic types also appeared in lesser numbers, though more abundantly with 15% than with 25% salt. Media containing lower concentrations of salt were unsuited to the isolation of the red organisms, permitting only a haphazard growth of contaminants which are suppressed by higher amounts of salt. Medium *B*, of the type frequently used for isolating organisms associated with reddening of salt fish, likewise permitted the growth of red halophiles, though less abundantly than Medium *A*. From both red and colorless colonies several strains were purified by replating three times on Medium *A* with 20% salt. Morphological and physiological comparisons of these purified strains indicated but one species of each type, a red sarcina (Culture 90-R5) and a non-chromogenic, non-sporing rod (Culture 90-N2).

The discoloration of Canadian cowhide was of a deeper reddish tint than that of Argentine hide, while the microscopic examination revealed a less uniform bacterial flora, which consisted mostly of rod-shaped organisms of various sizes with a small number of coccoid forms. That the organisms responsible for the reddening differed from those on the Argentine hide was further suggested by the cultural examination. Medium *A* (with 15 to 25% salt), which had been well adapted for the isolation of the red organisms in the latter, proved unsuitable for growing the red types on the cowhide, though it permitted good development of non-chromogenic organisms. On Medium *B* (with 20-25% salt) however, red growth occurred, appearing first after one week's incubation at 37° C. as small round pink colonies which gradually increased in size and deepened in color with age. It is of interest to note that on the fish medium (Medium *B*) little or no growth of non-chromogenic halophiles occurred so that the two media thus tend to be reciprocally selective for the two types of organisms. Microscopic examination of the red colonies showed rod forms with much pleomorphism, necessitating the use of a salt solution of approximately 20% for satisfactory observation. Mixed in water or weak salt solution, the organisms formed a viscous mass owing to distortion and rupture of the cells from plasmoptysis. Comparison of the isolated halophilic strains indicated one red type (Culture 91-R6) and two non-chromogenic rods (Cultures 91-N2 and 91-N4).

On buffalo hide the discoloration was slightly deeper in shade than that on the cowhide, though the microscopic picture was very similar, showing mostly rods of varied morphology with a smaller number of cocci. Media *A*

and *C* were used for isolation, the latter having been found superior to Medium *B* for culturing organisms of the pleomorphic rod type isolated from cowhide. As before, Medium *A* with 20% salt gave good growth of non-chromogenic halophiles together with smaller numbers of reddish colonies similar in type, though paler in color, to the sarcinae from the Argentine hide. On the milk salt agar (Medium *C*) with 24% salt, however, the beginning of reddish growth could be seen, after four to five days at 37° C., increasing in intensity of color until an abundant growth of deep red colonies was observed. As growth increased there was a marked zone of clearing round the colonies, pointing to a proteolytic action on the casein of the medium. Growth of non-chromogenic halophiles was almost entirely absent on Medium *C*, while colonies of the pink sarcinae developing on Medium *A* were not seen. Five halophilic types in all were isolated from the buffalo hide, of which two were reddish organisms, a sarcina (Culture 63-R1) and a pleomorphic rod (Culture 63-R2). Two non-chromogenic rod forms (Cultures 63-N1 and 63-N4) and one sarcina (Culture 63-N2) were also found.

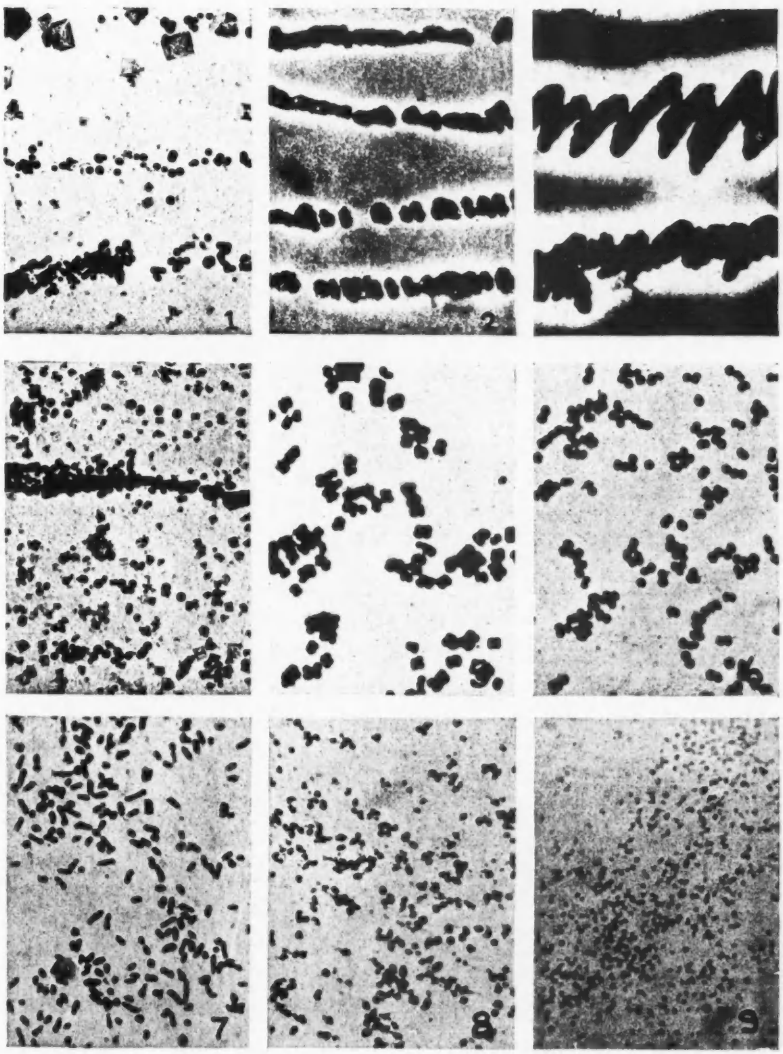
Red Halophilic Organisms

Culture 90-R5 (Sarcina litoralis Poulsen)

This organism, considered as the cause of red discoloration on the Argentine hide, is a large coccus. Cells may occur singly, in pairs, in fours, in short chains or in packets formed by division in three planes, the arrangement varying with such factors as medium, temperature, salt concentration and age of the culture (Plate I, Figs. 5 and 6). In young cultures (five days, 37° C.) on Medium *A* with 20% sodium chloride, cells vary from 1.2 to 1.6 μ in diameter with an average of 1.3 μ. There is a slight increase in size with higher salt concentration. The temperature of incubation has little effect on the size of the cells, though at temperatures of 20° or 28° C. there is more tendency to grow in packet formation than at 37° C. Less favorable salt concentrations likewise favor the sarcina form and larger packets. Medium *C* favors the growth of single cells, pairs, fours, and short chains more than the packet form (Plate I, Fig. 6).

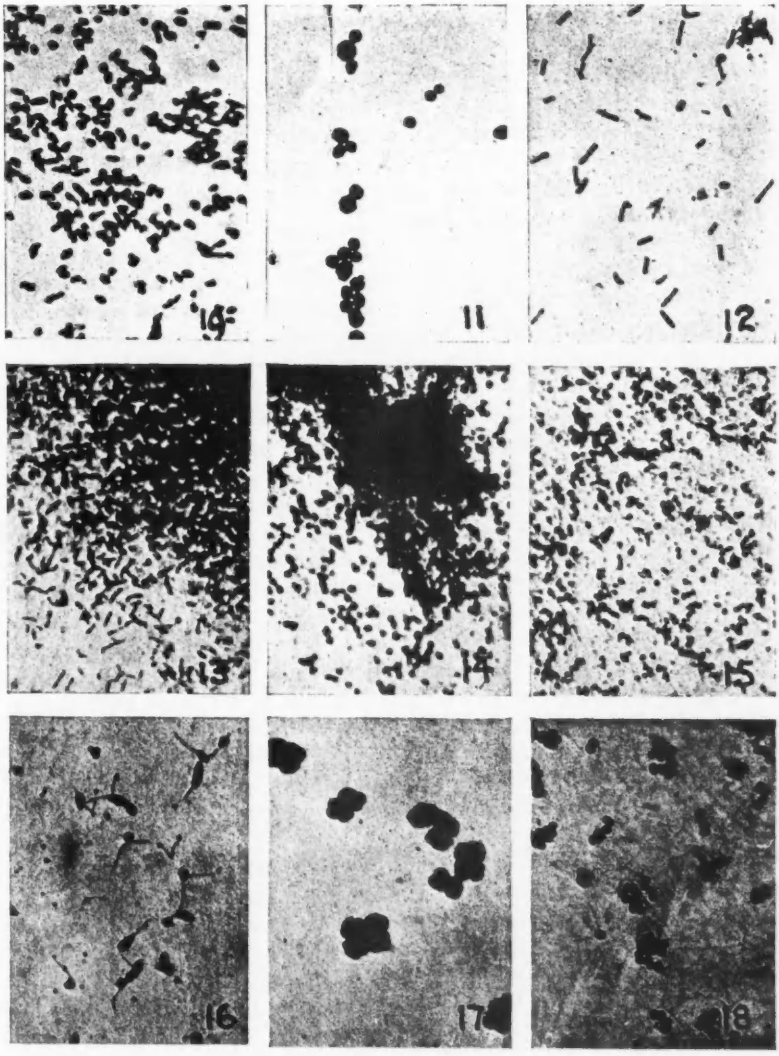
The organism is non-motile, non-sporulating, and stains well with ordinary dyes. The reaction to the Gram stain is variable, with a rather larger proportion of positive than negative cells. It is an obligate halophile, growing at a salt range of 16 to 32% with an optimum of 20-24% sodium chloride. It is an obligate aerobe, with a temperature optimum of 37° C.

On Medium *A* with 20% salt at 37° C. the organism develops after three to four days. Nearly colorless at first the growth deepens in shade as it increases in size. Colonies are usually 1–3 mm. in diameter, round, entire, convex, with a waxy appearance, brick red with a pale border (Plate I, Fig. 1). Slant cultures are filiform, slightly raised, with entire edge and with a color indicated by Ridgway (16) as "coral red". There is a slight decrease in intensity of shade as the sodium chloride concentration and the temperature depart from the optima.



Magnification:—Figs. 1–4 natural size, others × 1000. Stain:—fuchsin, unless otherwise stated.

FIG. 1. *Sarcina litoralis. Colonies, beef-yeast extract agar, 20% salt, 4 weeks.* FIG. 2. *Serratia salinaria. Milk agar plate culture, 24% salt, 4 weeks, showing proteolysis.* FIG. 3. *Serratia cutirubra. Milk agar plate culture, 24% salt, 4 weeks, showing marked proteolysis.* FIG. 4. *Sarcina sp. (Cult. 63-R1.) Colonies, beef-yeast extract agar, 20% salt, 4 weeks.* FIG. 5. *Sarcina litoralis. Beef-yeast extract agar, 20% salt, 15 days, 28°. Packet form.* FIG. 6. *S. litoralis. Milk agar, 20% salt, 13 days. Staphylococcal form.* FIG. 7. *Serratia salinaria. Milk agar, 24% salt, 5 days, 37°. Rods in young culture.* FIG. 8. *Ser. salinaria. Milk agar, 24% salt, 14 weeks. Coccoid forms, old culture.* FIG. 9. *Ser. salinaria. Milk agar, 20% salt, 10 days. Small cocci, dwarfed growth (Giemsa stain).*



Magnification, × 1000. Stain:—fuchsin, unless otherwise stated.

FIG. 10. *Ser. salinaria. Milk agar, 28% salt, 10 days. Rod form, staining irregularly.* FIG. 11. *Ser. salinaria. Starch agar, 20% salt, 3 weeks. Large coccoid form (Gonidangia) with budding.* FIG. 12. *Serratia cutirubra. Milk agar, 24% salt, 5 days, 37°. Rods.* FIG. 13. *Ser. cutirubra. Milk agar, 32% salt, 10 days. Rod forms disintegrating and coalescing to form symplastic mass.* FIG. 14. *Ser. cutirubra. Milk agar, 28% salt, 10 days. Granular symplasm and coccoid form.* FIG. 15. *Ser. cutirubra. From inoculated hide, red area, 12 weeks, 20°. Small cocci.* FIG. 16. *Ser. cutirubra. Milk agar, 28% salt, 6 days, 37°. Flagella. (Muir-Pittfield stain).* FIG. 17. *Sarcina sp. (Cult. 63-R1.) Beef yeast-extract agar, 20% salt, 11 days, 20°. Packet form.* FIG. 18. *Sarcina sp. (Cult. 63-R1.) Milk agar, 20% salt, 18 days. Staphylococcal form.*

No growth is obtained on ordinary media. The organism grows, though less readily, on standard nutrient agar with 20% salt and on milk salt agar. On the latter there is no evidence of proteolysis. On salt gelatin growth is definite though slow, with no liquefaction. Diastatic action is negative. In lead acetate agar growth is very slight, though a slight blackening is evident near the surface. Nitrates are reduced to nitrites. On potato (in 20% sodium chloride) growth is very scanty, appearing as a slight chalky, pink development near the top. Liquid media are unsuited to the organism, growth being negative or extremely scanty even with suitable salt concentration. On salted calfskin it causes reddening after one week at 37° C.

This organism appears to be closely related to other sarcinae isolated from various salted products. Poulsen (15) first described the isolation of a large red, salt-loving coccus which he named *Sarcina litoralis*, with which *Sarcina morrhuae* Farlow (6), isolated from reddened codfish, is apparently identical. The organism studied by Kellerman (9) and designated by him *Micrococcus litoralis* (syn. *Sarcina litoralis* Poulsen) is likewise similar to the type here reported, though he found it appearing chiefly as diplococci and single cocci. As the arrangement of sarcinae may vary with the cultural conditions, however, this feature is not considered sufficient to warrant a change of generic name. Klebahn (10) reports the isolation of a large halophilic coccus from reddened codfish which he classified as *Sarcina morrhuae*, while more recently Liebert and Deerns (11) and Petter (14) also describe types likewise isolated from fish which they consider similar. Another closely related species is the halophilic "red coccus" isolated by Cloake (5) from salted fish with red discoloration, and which was found to occur in both staphylococcal and sarcinal form. Our sarcina appears, moreover, to be closely related to the red sarcinal strains isolated by Lloyd and coworkers (12, 17) from salted hides showing "red heat" and from marine curing salts of different origin. These were also strongly aerobic halophiles, growing best at 37° C. and nonliquefying.

It is apparent that red halophilic sarcinae, similar in type to the writer's organism from Argentine hide, have been isolated from various salted products. As far as a comparison of characteristics permits the writer is inclined to classify the type as *Sarcina litoralis* Poulsen, a name which has priority over the designation *Sarcina morrhuae* employed by various authors for evidently similar organisms.

Culture 91-R6. Serratia salinaria (Harrison and Kennedy) Bergey et al.

This organism, regarded as the active agent in the discoloration of salted cowhides examined, is highly pleomorphic (Plates I and II, Figs. 7-11). It may occur as long rods and as small or large cocci with a wide range of intermediate forms which may be oval or of irregular shape and of varying size. Young cultures on milk salt agar with 24 to 28% salt show abundant rod forms of varying length which grade into coccoid cells, the rods ranging from 1 to 6 μ in length and from 0.6 to 1.5 μ in width, and the diameter of the round cells varying from 0.8 to 1.4 μ (Plate I, Fig. 7). Rod forms are

relatively scarcer in older cultures; here round cells, more or less irregular in shape and size, predominate (Plate I, Fig. 8). The form and size of the cells are influenced by the nature of the basic medium, salt concentration and temperature. An increase in salt concentration results in a slight increase in cell size and tends to favor the elongated form. Increasing the temperature up to the optimum (37° C.) produces similar effects. In addition to the smaller vegetative cocci, larger round forms may occur, 4 to 7 μ in diameter, with a pronounced granular appearance, and which may break up into a granular symplasm. This stage may be seen readily where the organism is cultivated on a medium of coagulated egg albumin with salt and yeast extract.

Apart from the methods of fission and also, apparently of upgrowth of regenerative units, the organism appears to be capable of reproducing by budding. This is observed on three-week cultures on starch agar with 20% salt, on which the organism grows slowly. Cultivated at 37° C., the organism forms large, round cells, apparently functioning as gonidangia, varying in diameter from 2 to 7 μ (Plate II, Fig. 11).

All stages of the organism are gram-negative. In the rod form it is motile while in young cultures oval cells and even round forms may be seen to be provided with flagella, indicating a stage in the life cycle analogous to that of the "swarmers" noted, *e.g.*, in *Rhizobium*. The oval or rod forms possess a single polar flagellum or frequently two flagella, one at each end, the motile coccoid forms showing a single organ. Flagella may reach a length of 10 μ. The large coccoid forms referred to above do not appear to be motile.

No growth of the organism occurs on ordinary media, and little or none even with the addition of salt. Special media are required, such as milk-salt agar, coagulated albumin (with yeast and salt), and fish-salt agar. Definite, though slow growth occurs on salt gelatin with beef and yeast extract. On milk-salt agar with 24% or more of salt, growth develops after three to four days at 37° C., pinkish at first but soon showing a definite red color corresponding to "scarlet" on Ridgway's chart. Colonies usually reach a diameter of 4 to 5 mm. Slant cultures are filiform, but slightly raised, with smooth, glistening surface and of butyrous consistency. As the culture ages a definite zone of proteolysis becomes apparent surrounding the growth (Plate I, Fig. 2). Cultures at this stage show an increase in pH value and a strong reaction for ammonia. There is also a characteristic putrefactive odor from such cultures, similar to that produced on calfhide by inoculation, in which case reddening occurs within four days at 28 to 37° C.

The organism develops at a range of 20 to 32% salt, with optimum growth between 28 and 32%. The temperature optimum is 37° C. The organism is an obligate aerobe. At 20° C. liquefaction of gelatin is slow but definite. Little or no growth occurs in liquid media. It does not reduce nitrates, nor does it exhibit any diastatic action. In stab cultures of lead acetate-salt agar there is but very scant growth with a trace of blackening near the top. No growth has been observed on potato.

A comparison of the morphological and cultural characteristics of the organism with those of reported red halophiles suggests identity with *Serratia salinaria* (8) found on reddened codfish. This latter organism showed not only similar pleomorphic forms, but exhibited closely similar physiological properties to such a degree that the two are regarded as specifically the same.

Culture 63-R2 Serratia cutirubra n.sp.

This organism, the causal agent of red discoloration on buffalo hides, is likewise pleomorphic (Plate II, Figs. 12-16). Young cultures on milk-salt agar (five days, 37° C.) showing forms varying from round cells, 1 to 1.5 μ in diameter, to rods 1.5 to 8 μ long by 0.7 to 1.4 μ wide (Plate II, Fig. 12). Rods predominate in young cultures, with older cultures showing an increasing proportion of coccoid forms. Apart from the question of age, the rod form is favored by higher salt concentration and by cultivation at 37° C. In the rod form the cells have a greater average length than *S. salinaria*. One-month cultures show almost exclusively coccoid cells, 0.8 to 1.5 μ in diameter, the appearance being very similar to that of the organism inoculated on to calfhide and incubated several weeks (Plate II, Fig. 15). Under certain conditions (*e.g.*, in milk agar with 32% salt) the organism, through disintegration of cells, forms a granular symplasm from which the granules or "regenerative units", by transference to a favorable environment, may form vegetative cells. As with *S. salinaria*, there is indication of a further mode of reproduction by budding of large coccoid cells, 1 to 2 μ in diameter, noticeable on media on which growth is comparatively slight (*e.g.*, starch-salt agar). In the rod form the organism is motile by means of a single polar flagellum (Plate II, Fig. 16). Motility may be observed in coccoid cells in young, though not in old, cultures. The organism stains but moderately well with ordinary dyes, and is consistently gram-negative.

No growth occurs on ordinary media, nor on most ordinary media with salt. Special substrates are required for good development, the best of those tried being Medium *C*. On this it grows at a salt concentration range of 20% to saturation, developing best with 28 to 32%. At 37° C., growth appears after three to four days, showing first pinkish in color, but developing into a deeper color corresponding best to "rose dorée" of Ridgway. Single colonies may reach a diameter of 3–4 mm., round and slightly convex. Slant cultures show filiform growth, slightly spreading, rather flat with smooth, glistening surface and membraneous consistency. Apart from differences in color and consistency the organism is further distinguished from *S. salinaria* by its stronger proteolytic action on milk, giving a much more rapid and extensive zone of clearing (Plate I, Fig. 3). The odor is pronounced, similar to that when inoculated on hide, on which typical reddening begins after 4–5 days.

The organism grows moderately on salt-fish agar, coagulated albumin (with yeast and salt) and slightly on starch yeast-salt agar and salt gelatin. Liquefaction of gelatin is pronounced. Nitrates are not reduced, diastatic action is negative while no indication of carbohydrate fermentation is seen. Indol is not formed. Little or no growth occurs in liquid media. The organism is an obligate aerobe, with a temperature optimum of 37° C.

While the organism is of the same group as *S. salinaria* it shows consistent differences in morphology and cultural character, particularly as regards color and consistency. These features, in addition to its more active proteolytic properties, appear to justify separate classification, and consequently the name *Serratia cutirubra* n.sp. is suggested for the species.

Technical description—Serratia cutirubra n.sp.

Pleomorphic rod, occurring also as oval and coccoid forms and in symplastic stage; rods 1.5 to 8 μ long by 0.7 to 1.4 μ wide; cocci 1 to 2 μ in diameter; in young cultures motile with one polar flagellum; no spores; Gram-negative; obligate aerobe; obligate halophile growing in 20% sodium chloride to saturation, best from 28–32%; no growth on ordinary media; little or none in liquid media with salt; grows best on milk-salt agar or fish-salt agar with colonies round, reddish (rose dorée), convex, glistening, and membraneous; optimum temperature 37° C.; liquefies gelatin; digests casein; produces ammonia, and hydrogen sulphide; nitrates not reduced; indol not formed; diastase negative; no fermentation of carbohydrates; produces reddening on salted calfhide.

Culture 63-R1 Sarcina sp.

In addition to the organism just described, a reddish sarcinal type was isolated from discolored buffalo hide (Plate I, Fig. 4; Plate II, Figs. 17 and 18). Morphologically and physiologically it resembled *Sarcina litoralis*, tne active agent on Argentine hide. It differed from the latter in showing a paler shade of red in cultures, and in developing at a slightly lower maximum salt concentration, namely, 28%. Inoculation tests on salted calfhide did not produce reddening, and it is therefore not regarded as an active agent in causing this defect under practical conditions.

Non-chromogenic Halophiles

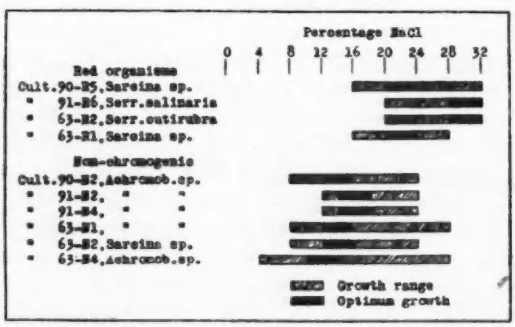


FIG 1. *Relation of salt concentration to growth of halophilic organisms from hides. (Percentage sodium chloride = gm. per 100 c.c. medium).*

In addition to the red halophiles, a number of non-chromogenic types were likewise isolated from the various discolored hides. Since this paper is concerned primarily with organisms producing red discoloration, a detailed description of their characteristics is omitted. The chief morphological and cultural features, however, are summarized in Table I (see also Fig. 1).

Observations

The question of the actual damage to hides caused by red discoloration appears to be a controversial one. It is probable that the injury depends upon the type of organisms concerned and particularly upon their proteolytic activity. Becker (2) regarded red discoloration as harmless since the organisms studied were non-liquefying. Furthermore Lloyd and coworkers found their red organisms to be likewise non-liquefying and less liable to damage the hide than proteolytic types. On the other hand, the signs of damage reported in Vestnik (1) were said to be attributable to proteolytic bacteria while Stather and Liebscher (20) found indication of definite injury.

The writer's observations support the view that hide injury in red discoloration is dependent on the proteolytic action of the bacteria. Thus in the case of the Argentine hide examined, the red organism, similar in type to those studied by Lloyd *et al.* (12, 17), was non-liquefying and did not show signs of proteolysis on hide. On the other hand, the two species of *Serratia* isolated from Canadian hides and both liquefying types, though in different degree, are considered capable of greater damage, inoculation on fresh salted hide resulting in definite proteolytic action. The non-chromogenic types isolated, some of which are liquefying, develop at a lower salt concentration range than the red organisms, and probably show little activity in a medium approaching saturation. While associative action with the red bacteria is possible, it was not indicated by inoculation tests.

TABLE I

CHARACTERISTICS OF NON-CHROMOGENIC HALOPHILIC ORGANISMS

Culture no.	Form	Size, μ (Med. *A*, 20% salt)	Motility	Spores	Gram stain	Opt. temp.	Growth on Med. *A* (with salt)	Growth on Med. *C* (with salt)	Salt conc. range, % (Med. *A*)	Opt. salt conc., %	Growth on potato (in brine)	Gelatin liq.	Nitrate red
90-N2	rod	0.6–5.0 ×0.4–0.5	–	–	±	37	+	–	8–24	12–16	–	+	–
91-N2	rod	1.0–4.0 ×0.4	+	–	–	37	+	–	12–24	16	–	+	–
91-N4	rod	0.3–3.5 ×0.5	+	–	±	37	+	–	12–24	16	–	+	–
63-N1	rod	1.2–3.5 ×0.4–0.5	+	–	–	37	+	sl.	8–28	12–16	+	–	+
63-N2	sarcina	1.0–1.2	–	–	±	30	+	–	8–24	12–16	–	–	–
63-N4	rod	1.4–4.0 ×0.6–0.7	+	–	–	28	+	sl.	4–28	12	–	–	–

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TRICHOGRAMMA MINUTUM RILEY AS A PARASITE OF THE ORIENTAL FRUIT MOTH (*LASPEYRESIA MOLESTA* BUSCK.) IN ONTARIO[1]

By W. E. van Steenburgh[2]

Abstract

The investigations described in this paper were carried out during the period 1928-1933, and deal with the egg parasite, *Trichogramma minutum* Riley, with special reference to its field of usefulness in the biological control of the oriental fruit moth (*Laspeyresia molesta* Busck.) in Ontario. This cosmopolitan parasite is a factor of considerable importance in regulating the abundance of the fruit moth in southern New Jersey, but appears to be of little practical significance in the natural control of the pest in Ontario. Under certain conditions of weather and host abundance, parasitism may be increased materially by the liberation of *Trichogramma* in the orchards but, in general, the results are not dependable. A large number of experiments were conducted utilizing three biological races of the species. The technique employed in the work and the results obtained are given as well as a number of important observations on the habits and biology of the parasite.

Introduction

The studies with *Trichogramma minutum* Riley, described in the following discussion, were undertaken to determine the usefulness of this small egg parasite as a factor in the biological control of the oriental fruit moth (*Laspeyresia molesta* Busck.) in Ontario. This serious pest was accidentally introduced into the Niagara Peninsula about 1922, and three years later was causing considerable damage to the peach crop in the vicinity of St. Davids, Ont. By 1927 the moth had spread over a large area and presented a serious problem to the peach growers of the district.

Trichogramma, a native insect, doubtless attacked eggs of the oriental fruit moth prior to 1928, when these studies were initiated, but its occurrence, so far as this host is concerned, had not been recorded, and little was known about the habits of the parasite, its actual distribution, or its importance as a control. The natural studies and liberations of the laboratory-bred material were undertaken to determine the value of the species under natural conditions and as a possible artificial control.

The original laboratory breeding stock of *Trichogramma* was obtained from Louisiana and California and belonged to Flanders' so-called "gray race". The field releases of 1928 and 1929 were made entirely with this strain. In 1930 and 1931, the native (yellow) race was reared in the laboratory and used in orchard releases. In 1931, an additional native strain, much darker in color (not listed by Flanders but studied by Martin (8) in Michigan), containing a varying percentage of wingless males, and found attacking the eggs of *Sialis infumata* Newm. in eastern Ontario, was used in the work. In 1932

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Contribution from the Dominion Parasite Laboratory, Entomological Branch, Department of Agriculture, Belleville, Ontario. A portion of this work was included in a thesis presented to the Committee on Graduate Studies, University of Toronto, in partial fulfilment of the requirements of the degree of Doctor of Philosophy.
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and 1933, the orchard releases were confined to the yellow indigenous race. Each race appeared biologically distinct and attempts to cross fertilize them failed. The laboratory and field studies showed considerable variation in activity and responses and indicated the possibility of each strain being suited to a particular environment. The developmental period of the races varied somewhat. At 80° F. the native yellow strain required eight days from egg to adult; the gray strain eight days and six hours; and the native dark strain slightly over nine days. In each case the parasitized host eggs became pigmented to a dull black during the third day.

The oriental fruit moth has three generations in Ontario, and in some years a partial fourth. The eggs of the first generation appear during the last two weeks of May and throughout June, with the maximum oviposition generally appearing in early June. The eggs of the second generation are deposited in July with the majority appearing during the latter half of the month. The maximum oviposition of the third generation appears in late August or early September and the hatching larvae enter the maturing fruit. It is the larvae of this generation which seriously damage the fruit. Eggs appearing at a later date in the season are of no consequence in fruit damage and are of no concern in this study except possibly as winter hosts for the parasite.

During most seasons, the indigenous *Trichogramma* do not attack eggs of the oriental fruit moth on peach until after the peak of the second generation of eggs and, therefore, have no opportunity materially to increase their numbers until the eggs of the third generation are on the foliage. The season is then too far advanced for an effective parasite population to develop. This natural handicap may possibly be overcome by the early colonization of laboratory reared parasites.

The efforts to secure control by the release of laboratory reared *Trichogramma* described in this paper are of an experimental nature. Suitable methods of colonization, the time of season best suited to the releases, and the number and distribution of the parasites within the orchards have been some of the more important subjects of study.

The Natural Appearance of *Trichogramma*

To secure a proper background for the experiments on colonization of laboratory reared *Trichogramma*, a knowledge of the seasonal appearance and normal abundance of the parasite in oriental fruit moth eggs was needed. This information was obtained by making weekly examinations of moth eggs at definite points through the infested area.

From 1928 to 1930 native *Trichogramma* was unimportant in reducing the numbers of eggs of the oriental fruit moth. This was chiefly due to its late appearance in the orchards, the small numbers of the first arrivals, and insufficient time to build up an effective parasite population. In these years only two or three generations of the parasite lived in this host before the fruit was picked. In 1931, field conditions were different. Native *Trichogramma* began its attack on eggs of the oriental fruit moth in early July and soon became abundant and remained an important factor of control through-

out the season. In 1932 and 1933 natural *Trichogramma* made an early appearance in the orchards, but with one exception was of little importance in reducing the injury caused by the pest.

Only two fruits in Niagara, the peach and quince, were consistently chosen for moth oviposition. During the earlier part of the season moth eggs were more abundant on quince, generally near the developing fruit where often as many as 30 or 40 eggs were found. With the exception of 1931 and 1932, there was a gradual decrease in preference for quince as the season advanced, with a corresponding increase in oviposition on peach. In 1931 and 1932, eggs were fairly plentiful on quince throughout the season and the usual increase on peach did not develop. In each year *Trichogramma* was abundant where host eggs were most plentiful.

Figs. 1 to 4* show the general trend of oviposition of the oriental fruit moth for the years 1928 to 1931, and, therefore, indicate the abundance of this host available for parasitism in the various egg generations. The information for the 1928 and 1931 graphs was taken from the St. Davids' records, while the 1929 and 1930 graphs were compiled from data collected at Virgil and Niagara-on-the-Lake. In general, the conditions at these points are very similar. The 1929 and 1930 records were taken from Virgil and Niagara-on-the-Lake so that no influence would be felt from the artificial colonization experiments at St. Davids.

A period, equivalent to part of a parasite generation before the first actual field record was taken, was allowed on the charts, since, in most cases, the parasite was in the later stages of development when first recorded. The curve for percentage of parasitism is drawn in proportion to the total number of host eggs present.

In 1928, *Trichogramma* was first taken parasitizing eggs of the oriental fruit moth on quince during the latter half of July. On July 23, 13% parasitism was found at Niagara-on-the-Lake. By August 10, a similar count at the same point showed 21%. The peach orchard at St. Davids failed to show the presence of the parasite on August 3, but a late count, made after the peaches were picked, showed 15%. Since, as will be shown later in the paper, the egg shells from which parasites emerge fall from the foliage sooner than do normally hatched eggs, it appears that the actual parasitism on the third generation of eggs would be at least 18 to 20%.

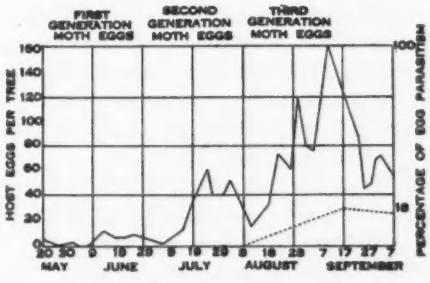

FIG. 1. *Oviposition of oriental fruit moth on peach and the natural parasitism by Trichogramma minutum Riley, 1928 (—— host, ... parasite).*

* *The egg graphs are a compilation of bait-pail moth catch and insectary oviposition records furnished by Mr. W. A. Ross and staff, Entomological Laboratory, Vineland Station, Ont., and egg counts secured from the foliage. The tree oviposition records and percentages of parasitism for 1928 were furnished by Mr. C. W. Smith.*

The first appearance of *Trichogramma* in eggs of the oriental fruit moth during 1929 was from quince at Niagara-on-the-Lake. Here, on July 29, the parasitism was 11·3%. A count made on peach foliage 100 yards away failed to show any parasitized eggs. *Trichogramma* was not found elsewhere in the district at this time. By August 14 the parasitism on quince foliage at Niagara-on-the-Lake had increased to 22%, while records from Queenston and Stamford showed respectively 13 and 18%. On August 15 a parasitism of 18% was found on peach foliage at Stamford, just across the highway from a quince planting. The following day a record from peach at Virgil showed 14% egg parasitism. By September 4 egg parasitism had increased to 20% at Virgil and was 16% at Niagara-on-the-Lake. The final counts made on eggs of the third generation, just previous to the picking of the late varieties of peaches, gave 40 to 45% parasitism at Virgil and 16% at Niagara-on-the-Lake. It should be noted that eggs were very plentiful in one of the Virgil orchards.

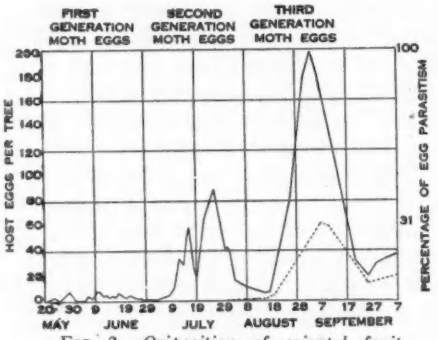

FIG. 2. *Oviposition of oriental fruit moth on peach and the natural parasitism by Trichogramma minutum Riley, 1929 (—— host, ... parasite).*

The field conditions during the first generation of the oriental fruit moth in 1930 pointed to the possibility of a heavy increase of eggs in the following generations. Dry weather, and the sudden appearance of large numbers of chrysopid larvae, on the peach and quince foliage, seriously affected its seasonal history. Instead of a sharp increase in egg abundance in the third generation, there were few more than during the second generation. This scarcity of host material and the presence of the predacious chrysopid larvae had a very retarding effect on the increase of the egg parasite so that, in many orchards, they were found only with difficulty.

The first seasonal record of *Trichogramma* was on quince at Niagara-on-the-Lake on July 16, when an egg parasitism of 5% was observed. Counts at other points did not show the presence of *Trichogramma*. By July 30 the parasitism on quince at Niagara-on-the-Lake had increased to 39%, which represents the highest record for parasitism for the year. Thereafter, it diminished on quince until at the same point on September 1 no parasitized eggs could be found. The first record on

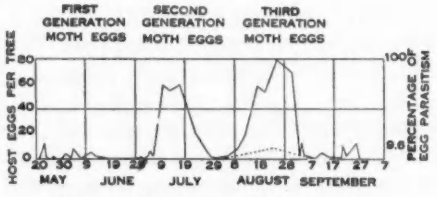

FIG. 3. *Oviposition of oriental fruit moth on peach and the natural parasitism by Trichogramma minutum Riley, 1930 (—— host, ... parasite).*

peach was on August 18, when a parasitism of 3.4% was obtained at Virgil; this increased to 13.3% just before the time of picking. *Trichogramma* was not secured from other points until the peak of eggs of the third generation, when 6% was found at Niagara-on-the-Lake.

In 1931, *Trichogramma* was seen parasitizing eggs on quince at Niagara-on-the-Lake on June 24, when 15% egg destruction was found. At this place egg parasitism had increased on quince to 42.5% by July 15. Thereafter, throughout the season, egg parasitism remained slightly over 30% on this fruit. The first record for peach was on July 9 at St. Davids, when 22.4% was recorded. By July 22 parasitism had reached 33%. This was the highest record secured until September 3, when egg parasitism reached 36.5%. *Trichogramma* was abundant everywhere throughout the peach growing district and was an important factor in moth egg destruction.

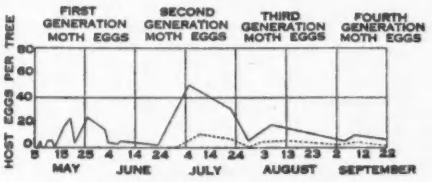

FIG. 4. *Oviposition of oriental fruit moth on peach and the natural parasitism by Trichogramma minutum Riley, 1931 (—— host, ... parasite).*

After 1931, the decreased number of eggs of the oriental fruit moth present in the orchards and the increased time spent in the colonization orchards made continued weekly observations difficult. Occasional observations gave the following information for 1932. Egg parasitism to the extent of 10% was found on the first eggs appearing on quince on June 1. It increased on quince until an egg parasitism of 38.3% was reached during the last week of June, after which it progressively diminished throughout the remainder of the season. On June 14 an egg parasitism of 7.7 and 15.9% was found in two peach orchards at St. Davids. In one of these orchards a collection of second generation eggs showed 27.2%, which was exceptionally high, as compared with the general average for the district of less than 5% on this generation of eggs. One heavily infested orchard near Hamilton showed a natural egg parasitism of 63.5% on third generation eggs, which was the highest record secured for natural *Trichogramma* throughout the study. In general, third generation egg parasitism this year varied between 0.0 and 23.0%.

In 1932, an experiment was designed to show the distribution of *Trichogramma* within an orchard in the early part of the season. A large orchard, adjacent to woodland, was chosen and egg examinations made at regular distances from the outside of the orchard inward. Two trees on the edge of the orchard gave 24.2 and 53.2% egg parasitism. Seventy-five yards from the edge of the orchard the parasitism had dropped to 12.2%, while the main body of the orchard, over 100 yards from the edge, gave 7.7%. A definite dispersal trend was apparent from the woodland into the orchard. This trend was also verified by the use of artificially placed *Sitotroga* eggs.

The first records of natural *Trichogramma* for 1933 were obtained on May 28 in peach orchards in the studies conducted with artificially placed *Sitotroga* eggs at St. Davids and Niagara-on-the-Lake. The highest percentage of egg parasitism observed was five, but even this low concentration would be sufficient to build up a parasite population which would be of importance in control. Such was not the case and later examinations in the same orchards toward the end of the first generation of host eggs failed to show any increase, and, throughout the remainder of the season *Trichogramma* continued to be of little importance. In this connection it should be noted that the moth infestation in this district was lower than in any year since the studies began. No orchard examined throughout the remainder of the season showed a higher egg parasitism than 15.7%, with the exception of the orchard mentioned for 1932 near Hamilton, and here a 28.8% parasitism was found on third generation eggs.

Trichogramma parasitism on quince was 24.7% at Niagara-on-the-Lake on June 13 and by July 9 the parasitism had increased to 31.4%. Throughout the remainder of the season a decreased activity was observed on this fruit.

In 1933, natural *Trichogramma* was of little value as a control agency. This decreased activity may, in part, be explained by the general decrease in the available eggs of the oriental fruit moth.

The activity of the native *Trichogramma* on eggs of the oriental fruit moth may be summarized in the following remarks:

(i) Only the native yellow race of *Trichogramma* appears naturally attacking this host.

(ii) *Trichogramma* is very irregular, both in its seasonal appearance and sectional distribution. It may be abundant in certain sections within a district and almost entirely absent in others. This was particularly noticeable in 1929, when the parasite was generally abundant, but showed a low concentration near Queenston and St. Davids. It is suggested that the abundance and distribution of native spring hosts regulates its later appearance in the orchards.

(iii) The percentage of egg parasitism varies considerably in different orchards and from year to year. This variation seems dependent upon two factors, (1) the degree of host infestation as expressed in egg abundance, and (2) the number of *Trichogramma* migrating into the orchards from native hosts. The latter factor has remained quite constant, with the exception of 1931, and, in general, the percentage of eggs destroyed has varied directly with the number of host eggs available. This is partly explained by the habits of the parasite. In the presence of an abundance of host eggs the movements of the female parasites are localized, but when eggs are scarce, most of the parasite's effectiveness is dissipated in rapid movements and migrations.

(iv). Except in years such as 1931, little assistance in the form of a high percentage of destruction of eggs of the oriental fruit moth is to be expected from the indigenous *Trichogramma*. It may play an important role in the more heavily infested orchards, but, on the whole, a high percentage of egg parasitism is not likely.

Overwintering

The following studies were conducted during the fall and winter months of 1928 and 1929, and 1929 and 1930 to determine the possibility of *Trichogramma* overwintering in eggs of the oriental fruit moth oviposited in late fall. The availability of this host offered the possibility of having a ready supply of *Trichogramma* for early emergence in the orchards.

The first series of studies consisted of fallen leaf collections made late in the fall of 1928 from different orchard situations as follows: (i) beneath the trees; (ii) from the sides and bottom of the orchard drainage ditches; (iii) from among the tall grass along the edges of the orchard. The leaves were stored in an open insectary until such time as they could be examined during the winter. From several thousands of leaves, only five unhatched parasitized eggs were found and these failed to emerge.

In the following year parasitized eggs of the oriental fruit moth of varying ages, reared at different temperatures, were exposed to the late fall and early winter climate. These had all perished by the first week of January. An examination of the dead parasites suggested death through desiccation.

Eggs of the oriental fruit moth do not appear to be a suitable overwintering host for *Trichogramma* in Ontario. The egg chorion is too fragile to protect the contents of the egg during such long periods of sub-development weather.

The Seasonal History of *Trichogramma*

This phase of the work was to provide a means of determining the number of life cycles of *Trichogramma* during the season, the possible number of generations following a colonization of material reared in the laboratory, and also the factors influencing the developmental rate. In 1929, successive generations of the gray race were reared on peach foliage, and in 1930 the work was repeated with the native yellow race. From a comparison of the results of these studies with the developmental curve of the parasite obtained from laboratory rearings at constant temperatures, it was shown that temperature was the only important weather factor influencing the rate of development. By comparing the mean temperatures for a particular period with the developmental curve, as obtained from the field life cycles and laboratory rearings, the number of possible generations of *Trichogramma* could readily be determined.

The time required for a cycle in the orchards at any given average temperature compared quite favorably with the laboratory rearings at constant temperatures, but were, in general, slightly longer in the orchards. This may have been due to the more exposed position of the instrument shelter, and the fact that the development of the parasite on the foliage may have been slightly retarded by the cooling effects of the normal leaf transpiration.

The field cycles were conducted in the following manner. A 20-mesh screened cylindrical cage, some 10 in. in diameter and 14 in. long, was used. This cage had an unbroken cloth covering over one end and a cloth sleeve fastener fitted to the other end. A suitable branch was chosen on a level

TABLE I

GENERATIONS REARED USING THE GRAY STRAIN, 1929

No.	Started	Emerged	Length in days	Mean temperature, °F.
1	May 16	June 17	32	59.3*
2	June 17	July 1	14	72.0
3	July 2	July 16	14	72.6
4	July 17	July 30	13	73.7
5	July 31	Aug. 18	18	67.2
6	Aug. 18	Sept. 2	15	70.7
7	Sept. 2	—	—	— **

** No. 1 was run with Ephestia eggs in the weather instrument shelter. Before May 16, there were only seven days with a mean temperature of over 50° F., which would allow little parasite development, since this temperature is close to the threshold of development for the species.*

*** This cycle had not emerged by September 15, when most of the peaches were picked.*

with the weather recording instruments and the screened cage was placed over the foliage. Female moths were introduced into the cage. When a suitable number of eggs was secured, the cage was removed and the *Trichogramma* adults liberated among the leaves. The eggs were then kept under observation until the next generation of parasites appeared. In obtaining the average mean temperatures for the developmental period, the daily mean for both the liberation day and the emergence day was included in the total average.

Table I shows the generations reared in 1929, using the gray strain.

It is seen from the rearings that there was a possible total of seven parasite cycles with six complete generations before the peaches were removed from the trees.

In 1930, the native strain was used for the life cycles. The first generation of the parasite was reared on *Ephestia* eggs in the weather instrument shelter, located in the orchard. Thereafter, the cycles were conducted on peach foliage. The generations are shown in Table II.

It will be seen that possibly there were eight effective generations of the parasite before the fruit was picked.

TABLE II

GENERATIONS REARED USING THE NATIVE YELLOW STRAIN, 1930

No.	Started	Emerged	Length in days	Mean temperature, °F.
1	May 1	June 3	33	59.5*
2	June 3	June 21	18	67.0
3	June 22	July 8	16	68.8
4	July 8	July 21	13	72.4
5	July 21	Aug. 1	11	75.2
6	Aug. 1	Aug. 13	12	74.2
7	Aug. 13	Aug. 30	17	68.5
8	Aug. 20	Sept. 17	18	67.6

** There were three isolated days before May 1 with a mean temperature above 50° F.*

No connection could be observed between the mean relative humidity and the development of *Trichogramma*, except in periods of slow development accompanied by low atmospheric moisture, and under such conditions that the host egg became desiccated and the enclosed parasite was killed.

The period of effective temperatures for *Trichogramma* in Ontario may be five months. Actually on the peach foliage, there are three and a half months during which *Trichogramma* may develop before the peaches are picked and during this period six to seven generations are possible.

The Factors Affecting the Development and Behavior of *Trichogramma*

The studies included under this general heading were designed in an effort to evaluate the various races of *Trichogramma* in regard to control of oriental fruit moth in Ontario, and also to assist in interpreting the activity of the parasite in the field. The investigations are a combination of laboratory and field studies. The laboratory work was conducted in specially constructed constant temperature incubators, and the field observations were made in the peach orchards.

The general habits of the native dark race made it appear unfit for orchard liberations, and the following studies were conducted entirely with the imported gray and the native yellow races.

Eggs of *Ephestia kuehniella* Zell. were used in the laboratory experiments.

The Developmental Period at Different Constant Temperatures

The laboratory observations on the developmental period at different constant temperatures were made for comparison with the mean developmental temperatures obtained in the field studies. The temperature stations were chosen at five-degree intervals from 50 to 100° F. Below 55 and above 95° F. no development was obtained. In the former case the eggs became desiccated and, therefore, 55° F. does not necessarily represent the temperature threshold of development. The results of these studies are shown in Fig. 5. For comparative purposes, the developmental curve of the yellow strain of southern New Jersey, as determined by Peterson (9, 10), is included. The same general developmental trend is shown, with the New Jersey strain requiring less time to reach the adult stage at the various temperatures.

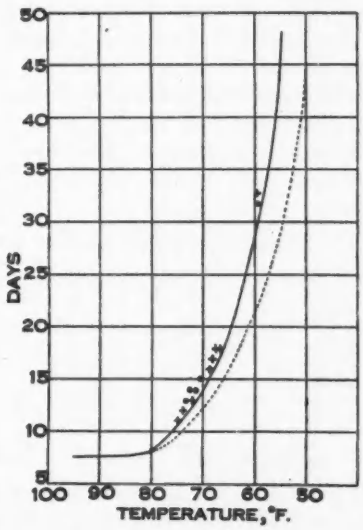

FIG. 5. *Developmental curve for Trichogramma minutum Riley. The solid line represents the developmental curve for the native yellow strain. The broken line represents a similar curve for the yellow strain of New Jersey for 1928 (Peterson). The points represent the gray strain reared in the orchard in 1929, and the crosses the yellow strain reared in the orchard in 1930.*

The gray race showed a slightly longer developmental period than the native yellow strain. This difference varied from several hours at the higher temperatures to slightly over a day in the lower temperature range. A close correlation was shown between the laboratory and field life cycles, which further substantiates the previous statement that temperature is the important factor determining rate of growth.

The females of the indigenous yellow race maintain their yellow coloration at all temperatures above 70° F. Below this, they show gray markings which become darker as the rearing temperature is lowered. The males of this strain show gray markings at all temperatures. The gray race retained its gray markings at all temperatures in both sexes.

Individual Female Ovipositions

Recently emerged females were isolated on embryological watch glasses 1½ by 4 cm. with ground glass tops which were held securely in place by elastic bands. The host eggs were pasted to a small round card which fitted part way down the concave sides of the dish. It was found convenient to face the eggs on the card downward and place a raisin between the upper surface of the card and the glass cover. The raisin provided food and moisture and was an important factor in offering a suitable environment. Parasites in dishes without such food soon perished, making much fewer ovipositions. The eggs were changed daily and new raisins were added as they became dry. A constant light was used over the incubators throughout the experiments, and conditions, except for the temperature, were kept constant. The generations of the two strains (gray and yellow) were reared side by side under identical conditions. The stock supplying the females for the work was reared at 80° F. and only mated females were used.

TABLE III

TOTAL OVIPOSITIONS SECURED PER DAY FROM 12 ISOLATED FEMALES FOR EACH TEMPERATURE RANGE

Temp., °F.	Days																						Totals
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Yellow strain																								
100	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0
95	26	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	26
90	290	55	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	345
85	309	45	8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	362
80	255	171	67	25	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	520
75	282	128	107	41	6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	564
70	259	118	55	44	57	31	37	11	22	8	16	5	5	2	2	2	–	–	–	–	–	–	–	674
65	227	154	132	57	60	44	44	21	12	9	1	2	4	1	–	–	–	2	–	–	–	–	–	770
60	211	73	243	128	247	67	58	36	50	28	15	17	9	–	–	–	–	–	–	–	–	–	–	1182
55	95	55	47	23	22	19	27	10	27	7	16	10	17	10	11	5	6	7	9	8	2	1	1	435
																								4878
Gray strain																								
100	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0
95	78	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	78
90	374	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	374
85	338	123	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	461
80	295	55	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	349
75	275	142	15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	432
70	415	80	15	3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	543
65	284	67	19	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	370
60	217	108	20	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	346
55	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0
																								2953

No blackened eggs were observed from which *Ephestia* larvae emerged. This was also true of the breeding work done with eggs of the oriental fruit moth. All blackened eggs represented killed host eggs. This is at variance with the findings of Schultze (1926).

The ovipositions of 12 isolated females are taken as representing the average for each race at each of the 10 temperature stations chosen, and to save space these are totalled by days in Tables III and IV.

TABLE IV

SUMMARY OF REARING AT DIFFERENT CONSTANT TEMPERATURES

Temperature, °F.	Oviposition			Length of life, days		
	Average*	Maximum	Minimum	Average*	Maximum	Minimum
Yellow *Trichogramma*						
55	36.2	43	27	23.0	32	9
60	98.4	166	43	15.2	23	4
65	64.1	101	36	12.6	21	2
70	56.1	123	23	8.0	16	2
75	47.0	83	22	4.0	6	2
80	43.3	62	17	3.5	6	2
85	30.2	60	11	1.5	3	1
90	28.8	60	4	1.2	2	1
95	2.1	12	—	—	—	—
100	—	—	—	—	—	—
Gray *Trichogramma*						
55	—	—	—	4.0	6	1
60	29.0	56	2	2.7	4	1
65	30.8	57	18	2.3	3	1
70	45.0	62	22	2.1	5	1
75	35.8	48	12	2.0	3	1
80	29.0	42	13	1.3	2	1
85	38.4	51	20	1.5	2	1
90	32.0	40	22	1.0	2	1
95	5.5	16	—	1.0	1	1
100	—	—	—	—	—	—

A consideration of the relation of the two strains to temperature suggests that the native strain is the better adapted for activity within the lower seasonal temperatures, and the gray strain better suited to the higher mid-summer ranges. The native strain produces its maximum oviposition near 60° F., while the southern strain reaches its greatest efficiency some 10 degrees higher.

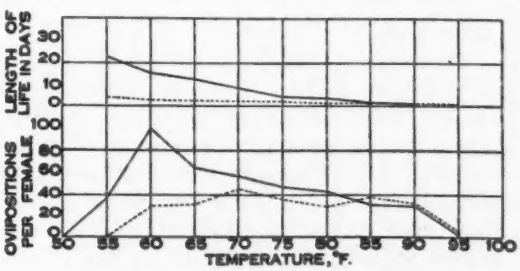

FIG. 6. *Curves showing the average life and average ovipositions of Trichogramma minutum Riley. The upper curves represent the average life of the strains, the lower curves the average ovipositions as taken from 12 isolated females (—— native strain, ... gray strain).*

TABLE V

THE AVERAGE PERCENTAGE OF FEMALES OBTAINED FROM THE INDIVIDUAL REARINGS AT THE DIFFERENT CONSTANT TEMPERATURES

Temp., °F.	55	60	65	70	75	80	85	90
Yellow females, %	62	61	64	73	64	63	65	61
Gray females, %	—	63	66	65	65	70	67	64

No particular trend in the relative numbers of males and females was observed throughout the experimental temperature range.

Storage of Parasitized Host Eggs

During the course of the laboratory work, various lots of parasitized *Ephestia* eggs were placed in cold storage chambers, ranging in temperature from 20 to 50° F. Unfortunately there were no means of determining or stabilizing the moisture content of the apparatus, and it was not possible to take this factor into consideration. Recently deposited parasite eggs remained healthy within the host eggs for a period of three days at 30 to 32° F., but after this time showed a mortality which increased rapidly with the length of storage. Developing parasite larvae within host eggs continued their growth after seven days' storage at the above temperature, but with longer periods showed an increasing mortality. In this case, death appeared to be due to the desiccation of the host eggs which often completely collapsed. More satisfactory results were obtained by allowing the developing parasite to reach the pupal state before placing the host eggs in storage, but it was also found that temperatures ranging between 35 and 45° F. gave much lower mortality. Under these conditions satisfactory emergence was obtained after a storage period of 75 days, although the emerging females laid only half as many eggs as those allowed to develop normally.

Because of the small amount of yolk and the relatively delicate chorion of eggs of *Ephestia kuehniella* Zell. they are not a very satisfactory host for holding *Trichogramma* in storage for long periods of time, and much healthier *Trichogramma* adults were obtained from these eggs when development was merely retarded by rearing at a temperature slightly above 55° F.

Adult Activity

The following observations are recorded as indicating the activity of *Trichogramma* adults. The information was obtained from three main sources: (i) from seven releases of 2500 *Trichogramma;* three of the gray strain and four of the yellow strain (the activity of the parasites was observed throughout the day of the release and the following day, and notes were kept on the rate and type of activity and the weather conditions); (ii) from the observations made during and subsequent to the larger colonizations; (iii) from studies made under controlled conditions in the laboratory.

Considerable difference in the activity and habits of the two strains under consideration were noted. The gray race was more active, took wing more readily, and was more rapid in dispersal. The yellow race moved more consistently by crawling and flights were of shorter duration. Generally, these flights were between nearby leaves. In the absence of host material both

strains were restless and rapidly dispersed. An examination of the foliage of a tree containing only a few eggs 24 hr. after a release of 2500 gray parasites, showed that they had completely disappeared. In another case where numerous eggs had been artificially planted on the foliage, gray *Trichogramma* were present the day following the colonization.

During the summer, the general activity of both strains seemed regulated by the abundance of host material present and the intensity of light.

The influence of light. Light intensity is the most important factor affecting the activity of *Trichogramma* in the field. The insect is positively phototropic and moves toward natural light even in the presence of much stronger artificial light. A knowledge of its activity in different light intensities may be used to advantage in interpreting its behavior on the foliage. Some idea of the insects' reaction to light may be shown by the results of an experiment conducted in an apparatus which allowed a range of temperature from normal (55 to 85° F.) to lethal (115° F.). Native yellow *Trichogramma* were placed in a glass tube four feet long, and allowed freedom in choosing the temperature they preferred. By darkening the tube in the lower ranges of temperature and applying a strong light on the part containing the lethal temperature, it proved possible to attract the insects into the higher temperatures where they died rather than return to the darkened areas.

Parasitized host eggs from which the parasites were due to emerge within an hour were placed outside at dusk and their emergence was thus delayed until sunrise the following morning. As the sun's rays intensified, the parasites rapidly left the host eggs. Under such circumstances the lower night temperatures also assist in retarding the emergence, but light was the important factor since emergence may be delayed several hours at a constant temperature by placing the parasitized eggs in total darkness. This retarding effect of darkness was used to advantage in making the larger liberations. The laboratory breeding of the parasite was so arranged that emergence was due to begin some time during the evening or night before the liberation was desired. The cards containing the parasitized host eggs were sealed into the waxed paper cones and these were hung in the liberation trees during the afternoon previous to normal emergence. The *Trichogramma* adults began to emerge shortly after sunrise the following morning, and were advantageously placed to attack the eggs of the oriental fruit moth deposited on the foliage during the previous evening.

Orchard observations on the activity of the parasite in exposed situations suggest a changed rate of activity when a cloud passes in front of the sun. Ordinarily on peach leaves a less marked reaction is noted. This is probably due to the diffused condition of the light produced by passage through the foliage. The insect does not seem to be so directly stimulated by the varying light intensities when in the body of the tree, and passes readily in all directions on the limbs and foliage, in fact, the greater majority of the parasites are to be found on the under surfaces of the leaves. Its activities in this case are probably influenced by its search for host eggs.

Intensity of light has a stimulating effect on them, which was especially noticeable during the liberation of laboratory-reared material. On dull days the insects rarely took flight unless disturbed, while on bright days adults were often observed to take flight, in fact, this appeared to be the desired means of transportation. The latter was particularly true of the gray race. When moving normally about on the leaves, the flights were of short distances, seldom over seven inches, although often the insects flew much greater distances. *Trichogramma* released in exposed locations reacted very definitely to the light intensity and immediately took flight. They appeared to leap free of the surface on which they were resting and rise some 10 to 16 in. before assuming any definite direction. In the absence of wind they disappeared in all directions.

All the observations indicate greater activity in the gray strain than in the native strain, and a tendency for wider dispersal.

The influence of wind. The direction and velocity of wind is a very important factor in the establishment and distribution of liberated *Trichogramma* within an orchard. The following observations illustrate the influence of air currents, but particularly the combined effects of wind and light intensity. A Petri dish containing 5000 emerged gray *Trichogramma* was placed in the lower unprotected portion of a tree between the larger divisions of the trunk. The top of the dish was partly removed to allow the parasites free access to the tree. With a temperature of 80° F. and alternating periods of sunlight and shade, produced by a cloud passing before the sun, the following observations were made.

When the sunlight was intense, the insects crawled from the dish and, after a short examination of their surroundings, took flight, generally flying upward in an erratic manner. The general direction of the flight seemed dependent upon the velocity of the wind. When a light breeze of one mile or less per hour was blowing, the flight was in a windward direction, probably veering either to the right or left of the wind course. When the velocity reached nearly three miles per hour, the insects were carried along with it. The behavior of the insect previous to, and during the beginning of, flight suggested that it headed into the wind and, when the velocity was greater than the speed of flight, was carried along with it. During the shaded periods the behavior of the insect was varied. On one such occasion a *Trichogramma* was observed to crawl 11 in. along a branch but this individual took wing soon after the appearance of the sun. Within an hour all the parasites had left the dish and none were observed to have crawled to the peach foliage 24 in. away, although *Trichogramma* were subsequently found on this branch. Dispersal from the liberation point was in all directions and the factor influencing the direction of flight appeared to be the direction and velocity of the wind.

The observations made in the orchards where large liberations were placed indicated that the later distribution and amount of oriental fruit moth egg

destruction depended in a large measure on the direction and velocity of the prevailing winds during, and directly following, the emergence of the *Trichogramma* from the laboratory host eggs.

The influence of precipitation. Only one opportunity was given to observe the activity of *Trichogramma* during a rainstorm, and while the foliage was still wet. In 1929 a heavy rainstorm blew up while the parasites were leaving the cones and considerable time was spent watching the reactions of the insects to the rain and the moist conditions of the limbs and foliage.

This was during the liberation of some 500,000 gray *Trichogramma* in a number of orchards. The temperature was 72° F., with little or no wind.

Except during the showers the insects continued to emerge slowly from the cones. Most of the parasites were crawling about on the cones or were perched on the under surfaces where they were protected from the rain. Some few were making their way onto the limbs and could be seen crawling about slowly. A few *Trichogramma* were observed four feet from the liberation cones, but these may have left the cones before the storm, since none were observed to crawl that distance during the period when the tree was very wet. No parasites were seen to take wing, although thousands were within short distances of the cones. Careful notice was taken to see whether the free moisture was detrimental to the *Trichogramma* and whether they became ensnared in the droplets as they do in free moisture in breeding containers in the laboratory. None were observed dead in the free moisture upon the limbs, but several were caught in fine spider's silk stretched between the coarse pieces of bark on the branches.

The observations suggest that rainstorms slow up the distribution of the *Trichogramma* within the tree and throughout the orchards, but otherwise do little damage. Probably, in a heavy storm, a number would suffer mechanical injury, but, on the whole, the parasites appear to be protected by the foliage.

The influence of predators and parasites. Few cases were observed where the adult *Trichogramma* suffered from the activity of enemies. Adults were observed enmeshed in the silken strands placed by spiders, but such cases were scarce, and, as far as the field observations could determine, few were destroyed by predators.

The developing parasites in the host eggs on the leaves were more exposed to attack. This was especially noticeable during 1930 and 1931, when great numbers of chrysopid larvae appeared on the peach foliage and remained throughout the season. A mortality as high as 60% was found in some of the orchards during the second generation of the oriental fruit moth in 1930. These voracious little chrysopid larvae thrust their mouthparts into the host eggs containing the *Trichogramma* larvae or pupae and suck the contents. One chrysopid larva was observed to destroy four eggs in 15 min. Because of the activity of these chrysopid larvae, both the oriental fruit moth and *Trichogramma* were greatly reduced in number.

It is also interesting to note that from 2 to 10% of the stalked eggs of the chrysopids were in turn parasitized by *Trichogramma*. The *Trichogramma* adult ascended the egg stalk and clung to the egg while ovipositing.

During these studies no secondary parasites were reared from parasitized eggs collected in the field.

The influence of artificial control. Observations made in orchards where oil or hydrate of lime was used as a spray or dust indicated that the normal activity of *Trichogramma* was inhibited when these substances were present on the foliage. Controlled experiments in a large glass container in the laboratory confirmed the field observations and showed that 75% more of the untreated eggs were parasitized than those sprayed or dusted. These substances were distasteful to the parasite and acted as a repellent and practically eliminated *Trichogramma* as a factor in egg destruction in such orchards. This probably explains why orchards sprayed or dusted often showed very little more control than untreated orchards.

The Orchard Activity of *Trichogramma* as Determined by Artificially placed Eggs of *Sitotroga Cereallela* Ol.

The many difficulties encountered in determining the actual numbers of eggs of the oriental fruit moth parasitized during any specific period in the experimental orchards suggested the use of artificially placed *Sitotroga* eggs. Their use was based on the assumption that fresh eggs placed in the trees and collected before hatching would give a fairly accurate picture of the activity of the *Trichogramma* during the period these eggs were available as hosts, and would also eliminate many of the factors which distorted the data secured from the examination of naturally oviposited eggs of the oriental fruit moth.

The *Sitotroga* eggs, some 50 in number, were fastened by shellac to small half-inch white tags provided with a string for attachment in the trees. The eggs used were under 12 hr. old and were transported to the orchard in a specially prepared refrigerator. The tags were numbered and securely tied in various places in the trees and accurate information kept as to their distribution. Throughout these studies, covering a period of two years, over 85,000 *Sitotroga* eggs were used.

Several objections were at once apparent to their use: (i) the concentration of the eggs on the card which facilitated parasitism by one female; (ii) the unnatural conditions offered by the cards; (iii) the influence of weather which would be more pronounced on such eggs; (iv) the species of eggs used were of a stored product insect in an unnatural environment; and (v) the eggs used were of the same species as that used for the laboratory breeding and introduces the possibility of host preference. After a consideration of these objections, it was decided to give this method of determining the activity of *Trichogramma* a trial. The results obtained justified their use and much information was obtained which could not otherwise have been secured.

The only strain of *Trichogramma* used in this work was the native yellow strain. For convenience, the results obtained from the various lots of *Sitotroga* eggs are grouped as follows: (i) the relative egg parasitism appearing in untreated orchards and colonized orchards; (ii) observations on the activity of *Trichogramma* in colonization orchards; (iii) comparative records of egg parasitism in *Sitotroga* eggs and natural eggs of the oriental fruit moth in the same orchard; (iv) parasite dispersals from isolated releases within an orchard; and (v) consideration of the possibility of *Trichogramma* showing a preference for the host on which it is reared previous to liberation.

Throughout the experiments the colonization orchards were treated from every third tree in each third row. In this manner there was only one space between any tree and a treated tree. Each group of cards placed in such orchards was exposed to approximately 18,500 *Trichogramma* to the acre, or from 1,600 to 1,700 parasites per release tree.

Results

1. The orchards receiving releases showed a much higher egg parasitism than the untreated orchards examined at the same time. The figures in Table VI illustrate this difference.

TABLE VI

PERCENTAGES OF EGG PARASITISM IN TREATED AND UNTREATED ORCHARDS

——	1	2	3	4	5
Colonization orchards, %	37.5	27.9	27.1	48.7	47.9
Untreated orchards, %	13.5 and 6.4	3.0 and 0.0	8.1	12.1	12.1

No. 1 record was obtained during the period when eggs of the first generation of oriental fruit moth were present, Nos. 2 and 3 during the presence of eggs of the second generation, and Nos. 4 and 5 during the presence of eggs of the third generation.

2. The records covering the activity of *Trichogramma* within the colonization orchards were collected from one-acre plots in which tags containing *Sitotroga* eggs were placed in every tree. The location of the cards was varied in the different trees and accurate record was kept of their location and subsequent history. The percentages of eggs parasitized on the liberation trees as well as those on the non-liberation trees, and the total for the plots are shown in Table VII.

TABLE VII

PERCENTAGES OF EGG PARASITISM ON LIBERATION AND NON-LIBERATION TREES

——	1	2	3	4	5	6	7
Liberation trees	50.6	35.2	57.4	42.7	60.4	64.0	79.3
Non-liberation trees	32.8	27.2	18.5	15.5	20.9	21.3	30.2
Total	36.5	28.6	20.9	23.5	29.3	42.5	35.2

The figures for Plots 1, 2, and 3, were obtained during 1932, and the remainder during 1933. These figures show a decidedly greater efficiency of the *Trichogramma* in the colonization trees, and indicate that for a uniform activity throughout an orchard, releases would have to be made from every tree.

The regional studies within the individual trees showed a general distribution of the parasites with slightly less eggs parasitized in the central part of the tree.

TABLE VIII

PERCENTAGES OF EGG PARASITISM ON NATURAL AND ARTIFICIALLY PLACED EGGS IN THE SAME ORCHARD

Natural eggs of the oriental fruit moth	Artificially placed eggs of *Sitotroga*
Eggs of first generation, 30.4	37.5 and 27.9
Eggs of second generation, 15.6	27.1
Eggs of third generation, 15.1	48.7
Eggs of third generation, 13.9	47.9
Eggs of third generation, 5.9	12.9

3. A comparison of the egg parasitism obtained in the colonization orchards between the artificially placed *Sitotroga* eggs and the natural eggs of the oriental fruit moth showed greater parasitism on the *Sitotroga* eggs. This discrepancy may be a result of a combination of the objections noted against the use of these eggs, or may, especially during the presence of eggs of the second and third generation of the oriental fruit moth, demonstrate the high dilution of natural eggs by old egg remains on the foliage.

The discrepancy increases with the season which suggests that remains of the eggs of the oriental fruit moth on the leaves may greatly influence the records and give a depreciated picture of *Trichogramma* activity.

4. The difficulty encountered in finding orchards where natural *Trichogramma* were entirely absent limited the number of dispersal studies which could be carried out from single releases. Such an orchard was found in 1933 and three releases of 1666, 5000 and 10,000 *Trichogramma* were made in widely separate parts of the orchard. Owing to the limited scope of the study, the records can be considered to indicate only a dispersal trend.

TABLE IX

EXTENT OF EGG PARASITISM OBTAINED IN DISPERSAL STUDIES FROM RELEASES OF DIFFERENT SIZES

Trees on which counts were made	No. of *Trichogramma* released			Trees on which counts were made	No. of *Trichogramma* released		
	1666	5000	10,000		1666	5000	10,000
	Eggs parasitized, %				Eggs parasitized, %		
Release tree	41.2	42.5	61.5	One tree south	0.0	0.0	19.1
One tree north	13.3	30.4	0.0	Two trees south	0.0	24.0	21.2
Two trees north	4.8	2.1	0.0	Three trees south	0.0	0.0	0.0
Three trees north	0.0	0.0	0.0	One tree west	0.0	0.0	12.1
One tree east	0.0	0.0	5.6	Two trees west	18.6	0.0	0.0
Two trees east	0.0	0.0	7.0	Three trees west	0.0	0.0	0.0
Three trees east	0.0	0.0	0.0				

These studies again indicate the increased activity of *Trichogramma* on the liberation trees, with a progressively higher parasitism as the size of the colony is increased. No reasons are apparent for the uneven dispersal of the parasites, since conditions throughout the orchard seemed uniform.

5. Throughout the studies conducted with *Sitotroga* eggs in the colonization orchards and untreated orchards there appeared a tendency for host preference. The newly released *Trichogramma* reared in the laboratory on *Sitotroga* eggs favored the artificially placed eggs, while the natural strain produced a higher egg parasitism on the normally oviposited eggs of the oriental fruit moth. The observations shown in Table X favor this contention.

TABLE X

PERCENTAGES OF EGG PARASITISM OBTAINED ON NATURAL EGGS AND ON THE LABORATORY HOST FOLLOWING ORCHARD RELEASES

Natural O.F.M. eggs, %	—	*Sitotroga* eggs, %
First generation		
30.4	Liberation orchard	37.5
15.9	Check	13.5
7.7	Check	6.4
12.2	Check	0.0
Second generation		
13.9	Three parasite generations after release	4.4
15.6	Liberation orchard	27.1
20.0	Check	8.1
Third generation		
12.0	Six parasite generations after release	7.5
15.1	Liberation orchard	48.7
13.9	Liberation orchard	47.9
17.7	Check	0.0

The data shown in Table X were obtained throughout the season of 1932. In as far as possible the records for the artificially placed eggs and the normal eggs were obtained from the same group of trees. The figures seem to indicate a tendency on the part of *Trichogramma* to parasitize the host species on which it matured. Should this evidence express a true tendency, it assists in explaining many of the unsatisfactory attempts to use this parasite in pest control.

Experimental Observations on Orchard Liberations

Methods of Liberation

The degree of parasitism secured in a particular tree, or even in an orchard, is not only dependent upon the number of parasites liberated and the abundance of the host eggs, but also, in a large measure, upon the time and manner in which the parasites are liberated. Observations made on the natural appearance of the parasite showed the dependence of the parasite on an abundance of host material for successful establishment and multiplication, which indicated that the desirable time to colonize was when eggs were abundant. In 1929 an attempt was made to release the *Trichogramma* two days before the expected peak of eggs for each generation. In 1930 and 1931 parasites of several ages were placed in the trees some two days before the expected peak of oviposition. The ages of the developing parasites within the laboratory host eggs were arranged to give a continuous emergence covering 10 to 14 days. In 1932 and 1933 a continuous emergence of *Trichogramma* was maintained during the various host egg generations.

Several methods were used for the release of the parasites in the orchards. As defects in one method became apparent, new ones were tried until a satisfactory technique of colonization was obtained. The following is a short description of the method considered as most suited to Ontario conditions.

The waxed paper cone type of release proved the most satisfactory. The parasitized host eggs were placed in a waxed paper drinking cone, and the bottom closed with a round card sealed in with a mixture of equal parts of beeswax and parawax. These cones are 3½ in. across the bottom and 5 in. high and, for field use, had a piece of string some 14 in. long threaded through the apex. The string served for attachment to the tree. Any number of *Trichogramma* of various ages could be sealed in the cone. For liberation, the cones were taken to the orchards and tied on the liberation trees, after which a small piece of the apex end was removed. The cones were light and could be easily carried in large numbers. The host eggs were protected both from the elements and most predators. Less than 5% of the cones showed the presence of predators, even after hanging on the trees for several days. All releases were made from this type of container after 1929. In 1932 and 1933 a smaller drinking cone, 2 in. in diameter, was used and attachment to the trees made with fine wire in place of string. This proved even more satisfactory, since the small cones were easier to ship and handle in the orchards.

Experimental Liberations

The following experiments were conducted during the seasons from 1929 to 1933, in the vicinity of St. Davids, Queenston, Niagara-on-the-Lake, and Grimsby. The points chosen each season for the work were in those districts where the infestation of the oriental fruit moth appeared to offer the best conditions for the work.

The work by Mr. C. W. Smith in 1928 showed a general trend in degree of parasitism proportional to the number of *Trichogramma* released, with very little control in the colonization tree, or those in the immediate vicinity, from liberations numbering less than 1000 parasites. His liberations were made from Petri dishes, which probably induced a much more rapid dissemination from the liberation tree than would be the case where the parasites were allowed to emerge from the laboratory host eggs at the point of colonization.

With an extension of the interest in control from the individual tree, and those nearby to the orchard, the rate of dispersal became an important factor, since the range and rapidity of dispersal would govern the number of colonization trees used in any particular area. An effort was made during the course of the work to determine this dispersal rate, which, unfortunately, seemed to vary to a considerable extent with the weather conditions during the emergence period.

Two courses of determining the amount of egg parasitism presented themselves; that of searching out the natural eggs on the foliage and determining the percentage of parasitism from the ratio found; or of placing twigs containing laboratory eggs in the trees and using the number of those attacked

as the index. It was felt that the first method, while much more laborious, represented the more natural and accurate method of determining the degree of egg parasitism, and it was, with one exception, used throughout this part of the study. Unfortunately, egg shells remained on the foliage for long periods, especially if there were no rains, and tended to dilute the counts and give a depreciated idea of the usefulness of the parasite. During 1929, marked shells remained on the foliage as long as seven weeks, while during the season of 1930 some of the shells laid by the overwintering generation of the moth remained all summer. Of 150 eggs deposited on June 11, 65 shells were still present in early September. This objection was somewhat overcome by studying the ovipositing habits of the moth for the successive generations and adapting the tree examinations to their changing habits. Also, the personal element is an important factor in evaluating the results obtained from the tree examinations. The monotony of examining leaf after leaf and the smallness of the eggs, coupled with the presence of old shells and the activity of egg predators, may have influenced the data obtained, but in general these factors tended to give an unfavorable impression of the activity of *Trichogramma*, rather than an exaggeration.

The first group of experiments was designed to show the degree of parasitism obtained on a known number of eggs. The limbs were enclosed in a cage with female moths. After a number of eggs had been oviposited, a liberation of adult yellow *Trichogramma* was made.

TABLE XI

PERCENTAGE OF EGG PARASITISM OBTAINED WITH A KNOWN NUMBER OF *Trichogramma* AND HOST EGGS IN 1930 (YELLOW STRAIN)

No.	No. *Trichogramma* released	Condition of sky	Temp. at time of release, °F.	Mean temp. for day, °F.	Wind velocity	No. host eggs	Total eggs parasitized	Parasitism, %
1	200	Clear	85	79.2	Moderate	77	46	59.7
2	200	Showers	65	69.9	Moderate	68	34	50.0
3	200	Overcast	84	73.8	Moderate	125	52	42.0
4	200	Overcast	87	82.2	Light	170	119	70.0
5	200	Showers	85	77.9	Moderate	150	64	43.0
6	200	Overcast	70	69.0	Light	260	247	95.0
7	200	Clear	78.5	67.6	Moderate	200	122	61.0
8	200	Overcast	81	73.6	Moderate	150	120	80.0
9	200	Showers	85	75.0	Moderate	70	52	75.0

NOTE: *In general the higher percentages of egg parasitism were secured when eggs were more plentiful and the sky overcast.*

The following group of experiments was conducted during 1929 in different orchards. Wherever possible, the liberations were made near the centre of the orchard. The release trees were separated from one another by a one-tree space, and the trees used for dispersal records were two trees removed from the nearest release.

The tree examinations were made from five to eight days following the release. All the unhatched eggs found during the first generation were reared. In the second and third generation counts the fresh eggs, averaging less than 10% of all eggs found, were discarded in figuring the percentages. To include the fresh eggs necessitated rearing all such eggs until they normally hatched or showed pigmentation denoting parasitism, and there was not sufficient time to make these individual observations.

TABLE XII

Trichogramma RELEASES IN 1929 (GRAY STRAIN USED)

No.	1st generation colonization	2nd generation colonization	No. colonization trees	No. trees examined	Host egg infestation	1st generation		2nd generation		3rd generation	
						Eggs found	Parasitism, %	Eggs found	Parasitism, %	Eggs found	Parasitism, %
1	70,000	—	7	11	Light	20	0	331	1.7	882	9.6
2	40,000	80,000	4	8	Heavy	39	2.6	382	7.6	987	66.5
3	—	225,000	20	26	Light	—	—	272	8.9	700	20.1
4	—	80,000	4	8	Heavy	—	—	330	15.1	1344	57.1
5	—	90,000	5	16	Medium	—	—	495	23.3	620	23.8*
6	—	61,000	4	12	Medium	—	—	303	9.1	794	40.0
Check	½ to ½ mile distant		—	9	Medium	—	—	—	—	820	16.1

* *Fruit picked at time of examination.*
No orchard liberations were made against eggs of the third generation.

The colonization trees and those nearby showed a higher egg parasitism during the egg generation on which the release was made. After one moth generation had passed, the *Trichogramma* became distributed throughout the orchard and the egg destruction on the colonization trees was no higher than on other trees.

The following experiments were conducted in 1930 with both the imported gray and the native yellow races of *Trichogramma*. A uniform number of parasites was used per acre throughout each individual orchard, but varying in the different experiments from 20,000 to 1,000,000 to the acre. No colonizations were made on the eggs of the first generation, since the studies of the previous year seemed to indicate a failure of the *Trichogramma* to become established when host eggs were scarce. The releases were made in 28 orchards covering some 250 acres, and 10,000,000 *Trichogramma* were used in the work. Because of the time required for tree examinations, it was not possible to trace intimately the results of the liberations in each orchard. The course followed was to trace carefully the *Trichogramma* establishment in a few orchards and to confine the examinations in the rest to the final generation of eggs.

The peculiar field conditions of 1930 made it particularly difficult for the parasites to become established and multiply because there was a relatively small increase in the numbers of moth eggs available in the successive generations (see Fig. 3). This condition may have been partly due to the dry

weather during the oviposition period, but in general was caused by the increase in larval parasitism and the great abundance of chrysopid larvae. These voracious larvae became numerous during the second egg generation and remained abundant throughout the season. They were very active on the peach foliage and destroyed large numbers of unhatched and parasitized moth eggs. This introduced a new source of error in interpreting the activity of *Trichogramma*, since most of the eggs were sucked before those parasitized became pigmented. In an effort to reduce this error, the conditions in each experimental orchard were studied and a conservative allowance made to cover this point.

In these experiments 10,000 *Trichogramma* were placed in each cone and the colonization trees were evenly distributed over the orchards.

TABLE XIII

Trichogramma RELEASES IN 1930 (GRAY AND YELLOW STRAINS USED)

No.	2nd generation release	3rd generation release	No. of *Trichogramma* per acre	Strains used	Host infestation	2nd generation			3rd generation		
						No. eggs	Chrysopid injury, %	Eggs parasitized, %	No. eggs	Chrysopid injury, %	Eggs parasitized, %
1			20,000	Yellow	Light	57	37	9.0	—	—	—
	2,030,000	2,030,000	20,000	Yellow	Light	87	50	9.0	—	—	—
2			20,000	Yellow	Medium	115	41	7.4	72	37.0	37.0
	1,600,000	1,600,000	40,000	Yellow	Medium	238	40	16.1	808	31.6	43.7
3	160,000	160,000	40,000	Yellow	Medium	—	—	—	123	11.4	42.0
4	100,000	—	50,000	Yellow	Medium	310	60	4.7	159	24.0	44.0
5	180,000	—	60,000	Yellow	Light	75	58	3.3	—	—	—
6	—	700,000	100,000	Yellow	Light	—	—	—	281	20.0	61.8
7	—	1,000,000	1,000,000	Yellow	Light	—	—	—	124	26.0	63.0
8	120,000	—	20,000	Gray	Light	99	51	44.0	—	—	—*
9	120,000	—	20,000	Gray	Light	85	38	29.0	—	—	—*
10	200,000	—	40,000	Gray	Light	196	51	23.3	112	12.4	29.0**
Check	Average of orchards ½ mile to 2½ miles distant					—	—	—	80	24.0	8.9

* *The parasitized eggs collected during the second generation tree examinations yielded gray Trichogramma.*

** *During the last generation collections of parasitized eggs, 90% of the females were of the gray strain.*

At the time of the third generation release, detached twigs containing eggs of the oriental fruit moth obtained in the insectary were hung in two colonization trees and in nearby trees at the different points of the compass.

These eggs were exposed to the first emergents from the cone, which represented one-quarter of the entire number released for this generation. When the twigs were collected, many of the leaves had wilted badly. The results are given in Table XIV.

TABLE XIV

EXTENT OF PARASITISM OBTAINED ON ARTIFICIALLY PLACED EGGS OF THE ORIENTAL FRUIT MOTH

——	Liberation trees	One tree removed	Two trees removed	Three trees removed	Four trees removed
No. of eggs	117	68	137	94	22
Extent of parasitism, %	44.6	37.5	37.7	24.3	0.0

The relation found with the artificially placed eggs of the oriental fruit moth was characteristic of the trend of the orchards generally. The greatest extent of egg parasitism was found on the colonization trees and those nearby and gradually decreased farther away.

Egg counts made 100 yards from the No. 7 plot showed a high parasite dispersal and 43% egg parasitism. The fruit examinations in the liberation plot showed 6.6% damage, while the trees where the dispersal egg examinations were made showed 11.6% damage. Fruit examinations made at picking time in experimental orchard No. 6 showed a fruit damage of 14.7%, while a count 150 yards away showed 26.8% fruit damage. The latter count was made in an orchard influenced by *Trichogramma* dispersal from the experimental orchard and cannot, therefore, be considered a reliable check. The average *Trichogramma* parasitism found in orchards in the vicinity of these plots was only 6%, which gives some idea of the absolute value of the liberations.

The experimental releases of 1931 consisted of 3,810,000 laboratory bred *Trichogramma* of the gray and yellow strains, and 5,000,000 of the native dark strain collected from eggs of *Sialis infumata* Newm. in eastern Ontario. The liberations were made in much the same manner as in 1930, except that generally throughout the season the yellow and gray strains were released in alternate cones. This mixing seemed advisable as a result of the laboratory observations on these strains. The native yellows are more active and prolific at lower temperatures (55 to 65° F.) and the imported grays showed greater activity and fertility at some 10° higher. By mixing the strains, it was hoped that advantage would be taken of weather fluctuations. Two orchards (6 and 7, Table XV) were used for pure releases of the yellows and grays. It was hoped that these would act as a check and also help to tie the work up with the previous years. One hundred thousand *Trichogramma*—half gray and half yellow—were obtained by the Dominion Entomologist from Dr. A. W. Morrill, of California, and these were used in a special experiment at Niagara-on-the-Lake to test out the gelatin capsule method for colonization.

Native *Trichogramma* appeared in the orchards (see Fig. 4) much earlier than in previous years and were plentiful throughout the season. Field studies indicated that their natural abundance was due to a large native host supply and migration into the orchards. This natural *Trichogramma* population was sufficiently large to maintain a fairly constant egg parasitism, which was relative to the host abundance in the various orchards, and it will be seen

TABLE XV

Trichogramma RELEASES IN 1931 (THREE STRAINS USED)

No.	2nd generation release	3rd generation release	No. of *Trichogramma* per acre	Strains used	Host infestation	2nd generation			3rd generation		
						No. eggs	Chrysopid injury, %	Eggs parasitized, %	No. eggs	Chrysopid injury, %	Eggs parasitized, %
1		70,000	40,000 50,000	Native dark	Medium	318	30	41.6	109	25	36.8
2	5,000,000	—	40,000 —	Native dark	Light	43	30	33.3	86	25	40.6
3		—	40,000 —	Native dark	Light	120	30	22.5	100	25	31.6
4			40,000 50,000	Mixed yellow and gray	Very light	22	30	19.0	—	—	—
5	1,300,000	2,040,000	40,000 50,000	Mixed yellow and gray	Very light	20	30	0	142	25	32.4
6	—	200,000	— 50,000	Yellow only	Light	—	—	—	116	25	52.2
7	—	200,000	— 50,000	Gray only	Light	—	—	—	76	25	35.5
Check	Average 5 orchards Queenston-St. Davids			Indigenous	Light	—	—	—	302	25	29.9
8	—	50,000	— 50,000	Yellow only	Light	—	—	—	102	25	31.1
9	—	50,000	— 50,000	Gray only	Light	—	—	—	109	25	29.1
Check	Niagara-on-the-Lake		—	Indigenous	Light	—	—	—	50	25	16.6

that the liberated laboratory stock did not greatly increase the numbers of *Trichogramma* already present. Also larval parasites were more active than in any previous year and chrysopid larvae were still destroying large numbers of eggs of the oriental fruit moth. These conditions resulted in a rapidly diminishing egg supply in the orchards after the second egg generation and rendered conditions particularly unsatisfactory for experimental liberations.

The colonizations were made in a continuous block including all the orchards between St. Davids and Queenston. This was done in an effort

to increase uniformly the parasite population over the entire experimental area and decrease the loss in parasite effectiveness by dispersal from the experimental area. As the season advanced it became apparent that the orchards were too widely separated to benefit from inter-dispersal between colonizations. To secure and maintain a high concentration of *Trichogramma* in orchards where eggs are scarce, as in 1931, would probably necessitate extensive parasite releases in areas between the peach orchards.

The releases were made uniform for the entire experimental area, 40,000 *Trichogramma* to the acre on eggs of the second generation and 50,000 *Trichogramma* to the acre on eggs of the third generation. The tree examinations were so arranged that the counts represent the general condition throughout the entire orchard. Not all the orchards received treatment in both generations.

The 70,000 individuals of the native dark strain, released in orchard No. 1 during the third egg generation, were reared in the laboratory. Orchards Nos. 1, 2 and 3 were in the area of heaviest infestation about St. Davids, where native *Trichogramma* were plentiful. Collections of parasitized eggs made during the egg generation of the release showed many eggs attacked by the dark strain, but collections made in the next egg generation yielded only the native yellow strain. Orchards Nos. 8 and 9 were used to test out the capsule method of colonization at Niagara-on-the-Lake. Four capsules, containing 100 parasites each, were placed to a tree throughout the entire plot. An increase in parasitism is noted as compared with the check.

The *Trichogramma* colonizations of 1932 consisted of 7,425,000 laboratory reared parasites of the yellow indigenous strain. This strain appeared normally year after year in the orchards, and even replaced the gray strain as the season advanced in the experimental orchards. Since it seemed much better adapted to Ontario conditions, it was decided to confine the releases to this strain.

The liberations were so arranged that a release cone was placed in each third tree in every third row. This provided 11 cones to the acre, and, with the exception of the first generation liberation, approximately 5000 *Trichogramma* were placed in each cone, thus providing slightly over 50,000 to the acre. The larger of the first generation colonizations was made with the idea of establishing the parasite in the orchard where it might gradually build up its numbers as the season advanced, and in this orchard 3500 *Trichogramma* were placed in each cone with the same number of cones to the acre. This experiment was similar in many respects to the first generation release of 1929, but, as the imported gray strain was used in that year, it seemed advisable to repeat the work with the yellow individuals. Beginning with the second generation, liberations were made with the object of direct control and three sets of cones were hung out during the presence of eggs of the second generation which provided a continuous emergence of parasites from July 4 to August 4. Four groups of cones were put out during the presence of eggs of the third generation, providing continuous emergence from August 16 to September 20.

TABLE XVI

Trichogramma RELEASES IN 1932 (YELLOW STRAIN USED)

No.	1st generation release	2nd generation release	3rd generation release	Host infestation	1st generation		2nd generation		3rd generation	
					No. eggs	Eggs parasitized, %	No. eggs	Eggs parasitized, %	No. eggs	Eggs parasitized, %
1	483,000	—	—	Medium	173	30.4	293	12.3	240	14.6
2	32,000	115,000	230,000	Light	—	—	50	18.2	169	18.3
3	—	249,000	2,250,000	Light	—	—	516	16.1	533	13.9
4	—			Light	—	—	224	6.5	123	15.5
5	—	—	565,000	Light	—	—	—	—	1294	8.9
6	—	—	1,260,000	Light	—	—	—	—	850	4.7
Check	—	—	—	—	39 25	15.9 10.7	55	5.9	50	4.1

The orchards chosen for the studies had sustained considerable injury due to the oriental fruit moth in 1931 and were located near St. Davids and Niagara-on-the-Lake. During 1932 the pest continued to diminish in numbers, principally owing to the activity of larval parasites, and consequently host eggs were scarce. In all the orchards under consideration the *Trichogramma* trend of previous years was apparent. Where host eggs were abundant a higher egg parasitism was obtained with fewer released *Trichogramma*, and where host eggs were scarce it was difficult to increase materially the mortality by large colonies of the parasite.

The *Trichogramma* releases of 1933 consisted of 2,621,000 parasites placed in a large orchard near Grimsby. The colonizations were moved to this new district so that a higher moth infestation might be available for the work since the severity of the damage from the pest was moving westward. The liberation technique developed in 1932 was used and a continuous emergence of parasites was maintained in the orchard between May 26 and June 30. As the season advanced, it became apparent that the orchard was poorly chosen as little injury due to the oriental fruit moth developed. Because of this reason and the need for economy the *Trichogramma* releases were discontinued in the Niagara district.

On the 10 trees examined during the period, only eight eggs of the oriental fruit moth were found of which one contained a developing *Trichogramma*. The figures given for 1933 for liberation orchards in the studies with artificially placed *Sitotroga* eggs were made in this experimental orchard, and show a high parasitism from the released *Trichogramma*.

A review of the data obtained from the orchards during the course of the investigations indicates that a number of factors influence the degree of control secured from *Trichogramma* liberations. The number of parasite releases is not the only item determining the ultimate amount of parasitism; in fact, the time and manner of liberations, the influence of weather conditions

on the strain used, and the abundance of host material may be even more important. In the presence of an abundant host supply fewer parasites will build up a greater extent of egg parasitism than will a substantially larger release where eggs are scarce. This was clearly demonstrated by the results obtained in 1929, as compared to those secured between 1930 and 1933. As the host supply diminished, a correspondingly larger number of *Trichogramma* was required to obtain an equal amount of egg destruction, and finally a point in host scarcity was reached after which even the largest numbers of liberated *Trichogramma* did not materially increase the egg parasitism.

Because of the interaction of the various ecological factors, it is not possible to foretell accurately, at any time in the season, the future abundance of eggs of the oriental fruit moth, or anticipate with any degree of certainty the amount of egg mortality which would result from a colonization of any given size.

Acknowledgments

The field work embodied in these investigations was conducted as part of the biological control program of the Dominion Entomological Branch, under the direction of Mr. A. B. Baird, in charge of the Dominion Parasite Laboratory, Belleville, Ont. The work was initiated by Mr. C. W. Smith, who conducted the field experiments in 1928. Assistance in securing the field records was rendered by various members of the staff, particularly in 1929 by Mr. Harry McGuffin; in 1930 and 1931 by Messrs. L. J. Briand and H. T. Clarke; and in 1932 and 1933 by Mr. H. T. Clarke, and especial thanks are due these men. The writer is also greatly indebted to Mr. George Wishart and Mr. L. R. Finlayson for the production of the laboratory material and its preparation and delivery to the field station. Thanks are due Mr. W. A. Ross and staff of the Dominion Entomological Laboratory at Vineland Station, Ont., and to Mr. G. G. Dustan, of the Ontario Entomological Department, for insectary oviposition records, meteorological records, and other valuable assistance.

The major portion of the laboratory experiments were conducted at the University of Toronto, and the writer wishes to thank Dr. E. M. Walker for kind criticism and advice during this work, and also in the preparation of this paper.

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NOTES ON THE CHLORIDES OF DIMETHYLANHYDRACETONE-BENZIL[1]

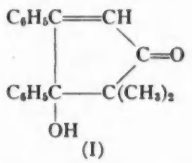
By C. F. H. Allen[2] and E. W. Spanagel[3]

Abstract

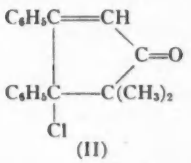
Some of the reactions of the tertiary chloride, obtained as a primary product by the action of thionyl or acetyl chloride on β, β-dimethylanhydracetonebenzil, are described.

Double decomposition reactions with cyclic unsaturated ketones like β, β-dimethylanhydracetonebenzil generally yield isomeric products, the nature of which vary with slight changes in experimental technique; consequently it is not surprising to find that the results obtained by one group of investigators do not agree in all respects with those found by another. In an earlier paper (1) certain reactions of the ketone I were determined as a side-issue, and the complete experimental details omitted for lack of space. Since some of the results were questioned (2), it seemed advisable to re-check them, as well as certain different ones recorded by Burton, Shoppee and Wilson (2).

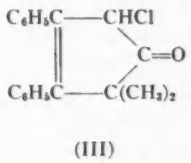
The principle product from the reaction of I with halogen compounds is the corresponding chloride, II; highest yields are obtained when acetyl chloride is employed (*cf.*, triphenyl carbinol).



(I)



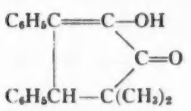
(II)



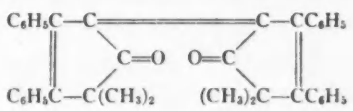
(III)

This chloride, however, is extremely easily isomerized by basic reagents to a substance which has been assigned the structure III, so the reactions of II may give products that result from either II or III. The isomeric chlorides are readily distinguished by silver nitrate, which gives an immediate precipitate of silver chloride with II, as would be expected of a tertiary chloride.

Hydrolysis of the chloride, II, in similar trials does not always give the same result; the hydroxyketone usually obtained has the structure IV,



(IV)



(V)

[1] *Manuscript received February 2, 1934.*
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but in some instances, small amounts of I have been isolated (best by use of aqueous-alcoholic potassium acetate) and sometimes a yellow bi-molecular product that has been represented as V (2). The substance V is very quickly destroyed by alkalies, but the nature of the reaction is uncertain—it does not give IV, traces of which can be detected by a color reaction with ferric chloride.

It seems advisable to record these results, with experimental details, since a complete investigation in this series is being made elsewhere (2). There seems to be no doubt of the structures of the substances represented by I, II, and IV, but the location of the double linkages in the other compounds of the series, described in this and other papers, cannot be considered as conclusively determined—an admittedly difficult if not impossible task.

Experimental

The chloride, II, was preferably obtained by dissolving the hydroxyketone, I, in a minimum amount of hot acetyl chloride and allowing the solution to evaporate in a current of air. The residue was recrystallized as described previously, the first crop being the desired substance. By the use of thionyl chloride as originally described (1), a reddish gum was obtained; this contained both chlorides II and III, which were separated by fractional crystallization. The isomer III agreed in all respects except melting point (120°C.) with the one described by Burton, Shoppee, and Wilson (they gave 126–127° C.).

An immediate precipitate was formed when six drops of a concentrated aqueous solution of silver nitrate was added to a hot alcoholic solution of the chloride II. A crystalline substance, melting at 120–122° C. and deflagrating when heated on nickel foil, was isolated after filtering the silver chloride, but it was not further investigated.

The action of alkalies on II causes isomerization to III, as well as giving rise to either isomeric hydroxyketone I, IV or the yellow bimolecular product V; while it is easy to secure IV (even by the use of alcoholic-aqueous potassium carbonate), the isolation of I and V must be regarded as fortuitous, because it was not found possible to obtain them at will (except I, by use of potassium acetate), even when reproducing the conditions exactly. Thus, the original ketone, I, was isolated only twice, in a small yield, by hand-picking the obviously different kinds of crystals; the yellow compound was obtained twice practically quantitatively and once in a small amount, using the same quantities of reactants that usually gave the ketone IV.*

The chloride II (0.1 gm.) was dissolved in 10 cc. of hot methyl alcohol, 10 drops of water added, followed by one drop of concentrated aqueous ammonia. After standing five days two kinds of crystals had formed and were separated mechanically. The prisms were unchanged chloride, m.p.

** All the reactions described here and previously have been carried out in alcohol containing water, which may account for the fact that different results were obtained by others (2) in very dry alcohol. By alcohol is meant 95% ethanol; all the methyl alcohol was the synthetic variety, used as purchased.*

and mixed m.p., 132° C. and the needles were the isomer, III, m.p. and mixed m.p., 120° C. The chloride II was recovered unchanged from a similar solution containing a drop of concentrated hydrochloric acid.

When equal weights of the chloride, II, and potassium acetate in aqueous methyl alcohol were refluxed a half hour the solution turned orange red and on evaporation left crystals embedded in a gum. The solid was separated and recrystallized twice from methyl alcohol; m.p. 181° C., mixed m.p. 182–183° C. This reaction was checked three times. The gum did not give a color with ferric chloride.

A mixture of 0.13 gm. of the chloride, II, 10 cc. of methyl alcohol, two drops of water, and 0.01 gm. of potassium hydroxide was refluxed 10 min. and allowed to evaporate to crystallization. After filtering and recrystallizing from methyl alcohol (followed by Skelly-Solve *B*, which did not change the melting point) it was identified as the chloride, III, m.p. 120° C., mixed melting point with II, 99–100° C. The same result was obtained by using a mixture of 0.4 gm. of II, 0.5 gm. of potassium hydroxide, two drops of water, and 25 cc. of methyl alcohol, but on refluxing a further 10 min., after adding 1.5 gm. of sodium hydroxide solution (1 cc. = 1 gm.) and filtering the salt that separated, the hydroxyketone, IV, was isolated from the filtrate.

The yellow compound, V, precipitated* when 0.4 gm. of sodium hydroxide solution (1 cc. = 1 gm.), 0.4 gm. of chloride, and 15 cc. of methyl alcohol were refluxed a few minutes. It turned red and melted as described in the literature (2). If the pure yellow compound was refluxed with alkali it slowly dissolved and after 50 min. the solution was practically colorless. It was acidified with acetic acid and a curdy precipitate, that separated on adding water, was separated by filtration. This dissolved readily in the ordinary solvents but separated as a gum. None of the solutions gave a color with ferric chloride.

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* *In two runs only; others gave IV.*

THE OXIDATION OF ALLYL ALCOHOL[1]

By W. H. Hatcher[2] and C. T. Mason[3]

Abstract

The oxidation of allyl alcohol by potassium permanganate in acid solution results in the formation of three molecules of formic acid; up to this point the successive steps involved are favored by acidity of the solution, such that the velocity of the reaction varies directly as the concentration of sulphuric acid. Also the rate of oxidation varies directly as the concentration of the oxidizing mixture. The most rapid part of the reaction is the absorption of the first six equivalents of oxygen, the slowest being that of the last six of the total of 16 concerned. A mechanism is suggested.

Introduction

In previous publications (2, 3) a method was outlined for discovering the mechanism of oxidation of organic compounds by potassium permanganate; this depends on following quantitatively the disappearance with time of the permanganate in dilute sulphuric acid solution in the presence of the substance to be oxidized. If the results be plotted against time for different concentrations of sulphuric acid, which in every case is in excess of that required stoichiometrically, the curves obtained are found to be analyzable into two main forms; one form shows the formation and oxidation of formic acid and the other the presence of a grouping similar in rate of oxidation to oxalic acid. This in brief is the generalization previously formulated.

Procedure

An accurately weighed quantity of the organic substance to be studied is dissolved in water and made up to a definite volume. An aliquot of this solution is then added to a definite volume of an aqueous solution of potassium permanganate and sulphuric acid, the former being in large excess of that required for complete oxidation to carbon dioxide and water of the organic substance, and the sulphuric acid in excess of that required by the permanganate. After standing at a constant temperature for the desired time, reaction is stopped by the addition of standard, dilute hydrogen peroxide. By back titration the volume of standard permanganate used up in oxidation is found.

Experimental

The best available allyl alcohol was used in these experiments but it was found necessary to purify it. This purification briefly consisted of standing in contact with ammoniacal silver nitrate in the absence of light and under an atmosphere of carbon dioxide, and of subsequent distillation in the same atmosphere. It was found that short contact with oxygen produced appre-

[1] *Manuscript received November 27, 1933.*
Contribution from the Department of Chemistry, McGill University, Montreal, Quebec, Canada.
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ciable quantities of acrolein, hence the necessity for these precautions. The purity of this allyl alcohol was checked by total oxidation by the method of Cameron and McEwan (1).

In addition, the usual care was taken to ensure purity of materials and manipulative accuracy.

Results

For the sake of brevity, the results are shown by tabulating the details of typical experiments, as shown in Table I, and by showing in Fig. 1 the curves in which appear the experimental results.

In the following table are given the experiment numbers, and the concentrations of the reagents, — allyl alcohol in gram molecules per litre, and potassium permanganate and sulphuric acid in gram-equivalents per litre. The temperature throughout is 25° C. and the total volume of reacting solution 250 cc.

TABLE I

MOLAR CONCENTRATIONS OF MIXTURES

Expt. no.	Concentrations		
	Alcohol	Permanganate	Sulphuric acid
1	0.0007	0.0011	0.0012
2	0.0007	0.0011	0.0024
3	0.0007	0.0011	0.0036
4	0.0005	0.0011	0.0012
5	0.0005	0.0011	0.0024

The curves shown in Fig. 1 bear the same numbers as the experiments above. Here equivalents of permanganate are plotted against time in minutes.

Complete oxidation of the molecule of allyl alcohol to carbon dioxide and water requires eight atoms of oxygen, *i.e.*, 16 equivalents. Each molecule of formic acid requires two equivalents for complete oxidation. Since hydrogen ion concentration is inimical to the rapid oxidation of formic acid, the rapid formation and slow oxidation of this acid is indicated by the curves tending to parallel the x-axis by two equivalents short of the 16 for each such molecule of formic acid.

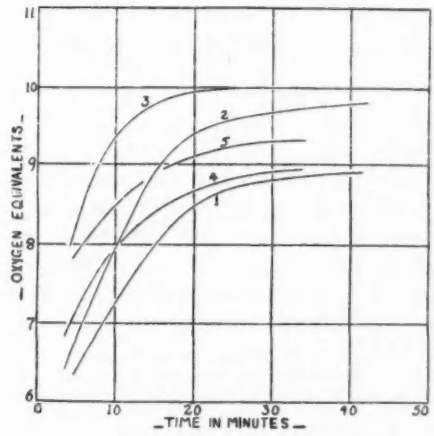

FIG. 1. *The oxidation of allyl alcohol by potassium permanganate.*

In these curves the maximum is in the vicinity of 10 equivalents, and all are above eight, with two equivalents for each formic acid molecule produced, the difference between 16 and 10 indicates the formation of three molecules of formic acid. The relative positions

of Curves 1, 2 and 3 and also of 4 and 5, show that the course of oxidation of allyl alcohol up to the formation of formic acid, is favored by acidity; this is of course accomplished in several steps not easily identified.

The presence of formic acid is further indicated by the progressive flattening as we proceed from Curves 1 to 3, and from 4 to 5.

From Curves 1, 2, 3 the times to half value—*viz.*, eight equivalents—indicate the velocity of the reaction to vary directly as the concentration of the sulphuric acid; the same holds for Curves 4 and 5. Approximately the same relation holds between the alcohol and the oxidation mixture, as seen by comparing Curves 1 and 4.

Finally, then, up to the formation of three molecules of formic acid, the oxidation of allyl alcohol by acid permanganate belongs to the oxalic acid type. The complete liberation of formic acid then superimposes itself upon the reaction velocity, causing a slow progress beyond 10 oxygen equivalents.

The entire steps may be suggested as follows. Allyl alcohol to glyceric aldehyde, either through aerolein or glycerol, then to glyceric acid; these steps represent the very rapid oxidation with absorption of six equivalents—as seen from the curves. From glyceric acid the steps would proceed to glycollic aldehyde with one formic acid stored up for slow oxidation; thence to glycollic acid which splits with oxidation to form two molecules of formic acid.

Confirmation of these ideas was obtained by examination of a reaction mixture when 10 equivalents of permanganate had been used up. Considerable formic acid was obtained but no other substance could be detected.

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THE SORPTION OF VAPORS BY ALUMINA

II. BENZENE[1]

By L. A. Munro[2] and F. M. G. Johnson[3]

Abstract

The sorption of benzene vapor by alumina gel has been measured over a range of temperature and concentration. It has been found that divergent sorption values obtained with gels differing in residual water approach a constant value when expressed per gram of active alumina. Straight lines are obtained when the logarithm of x/m is plotted against the logarithm of the vapor pressure. Patrick's equation is approximated for lower relative pressures. Comparison of the results obtained with benzene with those previously obtained with water fails to show that hydration or "chemical" forces play any part in the sorption of water by alumina. The gel holds a larger volume of liquid benzene at low partial pressures.

In a previous paper (11) the authors reported the results of an investigation on the sorption of water vapor by alumina gel over a range of temperatures and concentrations. The present paper presents a similar comparative study of the sorption of benzene vapor.

Benzene was chosen for comparison with water because, unlike the latter, it is a non-polar liquid. It is also easily dried and purified (8). Furthermore, it is known that alumina forms hydrates. Fricke and Wever (4) have found that amorphous alumina gel changes gradually at room temperature to hydrargillite, a hydrated form, and if kept at 100° C., the moist gel is converted to micro-crystalline bauxite. Weiser (13) and also Edwards and Tosterund (1) have recently reported X-ray studies of these pseudo-hydrates of alumina. With alumina then, some of the sorbed water may be "combined chemically", that is, there may be an additional force factor operative during the sorption of water vapor. It was thought that the comparison of these vapors might give information regarding the importance of "chemical" forces in sorption processes.

Apparatus and Method

The apparatus and method of study were the same as used in the previous study. Briefly, the method is as follows. Pure air is supplied at a definite rate by an automatic, thermostated Topler pump to a saturator, and thence to a second thermostat containing the alumina tube. The sorption is followed by weighing the alumina at intervals. An arrangement is provided whereby this is effected without removing the sorbent from the thermostat. For diagrams and a detailed study of the accuracy of the apparatus the reader is referred to the previous paper (11).

[1] *Manuscript received November 14, 1933.*

Contribution from the Department of Chemistry, McGill University, Montreal, and the Department of Chemistry, Queen's University, Kingston, Ontario, with financial assistance from the National Research Council of Canada and the Research Committee, Queen's University.

[2] *Assistant Professor of Chemistry, Queen's University, Kingston, Ontario, and holder, at the time, of a fellowship under the National Research Council of Canada.*

[3] *Dean of the Faculty of Graduate Studies and Research, and Director of the Department of Chemistry, McGill University.*

From the volume of entering air and the vapor pressure of the benzene, the amount of vapor supplied can be calculated. Curves are obtained by plotting amount supplied against the amount sorbed for each temperature and pressure. These show the efficiency of the alumina. They also give the saturation values for different partial pressures. Isotherms may then be constructed as with a static method of study.

Materials

Gel

The gel was prepared by precipitation from the hot nitrate solution with concentrated ammonium hydroxide, and subsequent dilution and boiling the suspension until it was free of excess ammonia. The precipitated gel was washed free of nitrates and dried at 100° C. for 24 hr. The total water content was determined by ignition overnight.

Before use a weighed amount of gel was activated at 300° C. for one hour. The residual water content of the sorbent was calculated from the loss in weight and the original water content.

Benzene

The benzene used was Baker's best grade. This was further purified by treatment with anhydrous calcium chloride and sodium wire. Before use a portion was siphoned off from the reservoir containing the sodium wire into an all-glass apparatus and the middle portion of the distillate used.

Calculation and Verification of Amount Supplied

The amount of benzene carried over was calculated from the vapor pressures, assuming complete saturation of the air, accurate temperature control, the validity of Dalton's and Avogadro's laws.

To check the amount of benzene supplied, the mixture was pumped into a U-tube of charcoal cooled with liquid air. Results were not satisfactory because the charcoal also sorbed large quantities of air which varied with the level of liquid air in the dewar. Again, the only charcoal then available caused considerable back pressure. Since the amount of benzene carried over depends on the pressure over the liquid in the saturator, it was determined to use a method of checking which avoided sorbents. Determination by condensation from the air stream was not entirely successful. Excellent check results were obtained by a delayed combustion method, in much less time than would be entailed in the preparation of suitable coarse sorbents.

In the latter method a known volume of gas-vapor mixture was pumped into one of a series of containers in an ice bath. The end container was connected to a furnace, the whole system being at 760 mm. pressure. The absorbing train was then attached to the furnace and the benzene carried by oxygen into the furnace in dilute concentration as the bath was allowed to warm up gradually.

A series of seven determinations of the amount supplied per hundred strokes of the pump at 30° C. gave an average of 0.772 gm. The apparatus had been rebuilt since the experiments with water, and the volume of the new pump was 13.42 cc. The theoretical amount is given by the expression $\frac{78}{22400} \times \frac{118}{642} \times \frac{273}{303} \times 1342 = 0.774$ gm. It was therefore assumed that the calculated amount was correct to within 0.5%. This was borne out by the subsequent sorption experiments as shown by the initial values given in Table II (60° C.—Columns 7 and 8; 10 and 11: 50° C.—Columns 1 and 2; 4 and 5).

Expression of Results

Sorption results have been reported in a number of ways. Several investigators have expressed their results as grams per gram of original gel. Most workers, however, have given the amount sorbed per gram of sorbent, which, if a hydrous oxide, contains residual water. It has been shown that sorption varies with the amount of water left in the gel. The writers have found this to be true of the sorption of ether (10) and water vapor by alumina gel. The sorption of benzene at 25° C. by alumina gels differing in residual water content is shown in Fig. 1, data for which are given in Table I (12). In this experiment the gel used was Baker's alumina containing 34.7% water.

TABLE I

THE EFFECT OF RESIDUAL WATER ON THE SORPTION OF BENZENE

No.	Initial weight, gm.	Activation conditions	Water lost on activation, gm.	Grams sorbent	Residual water, %	Weight of benzene sorbed, gm.	Grams active Al_2O_3	x/gm. sorbent	x/gm. active Al_2O_3
1	4.8888	150°—1 hr.	0.0026	4.8862	33.8	0.0016	0.0049	0.33	326.5
9	5.0010	200°—1 hr.	0.1104	4.8906	33.2	0.0135	0.2078	2.76	65.0
2	5.0096	220°—1 hr.	0.1960	4.8136	32.04	0.0198	0.3689	4.11	53.69
10	4.9898	250°—1 hr.	0.4061	4.5837	28.9	0.1470	0.7642	32.07	192.34
B	3.0642	185°—1 hr. 285°—1 hr.	0.3664	2.6978	25.8	0.1532	0.6895	56.8	222.2
3A	2.6000	290°—1 hr.	0.3803	2.2197	23.5	0.1613	0.7173	72.7	225.
D	2.534	295°—1 hr.	0.4012	2.1328	22.4	0.1892	0.7550	88.8	251.
A	3.0636	285°—1 hr.	0.5084	2.5552	21.7	0.2503	0.9567	97.95	262.
C	2.6962	285°—2 hr.	0.4913	2.2049	20.2	0.2284	0.9246	104.	247.
EA	2.6563	160°—3 hr. 300°—1 hr.	0.5434	2.1129	17.9	0.2682	1.0226	127.	262.
16	5.0845	300°—1 hr.	1.1485	3.9360	15.6	0.5494	2.1613	140.	254.
15	2.9896	300°—2 hr.	0.7234	2.2662	13.9	0.3450	1.3614	152.	253.
12	5.0035	350°—1 hr.	1.4058	3.5977	9.18	0.7027	2.6457	195.	266.
G	2.8190	350°—1 hr.	0.7920	2.0270	9.18	0.3938	1.4904	194.	264.
4A	3.0841	380°—1 hr.	0.8980	2.1861	7.88	0.4214	1.690	193.	249.
13	4.8742	385°—1 hr.	1.4760	3.3980	6.33	0.7381	2.7782	217.	266.
5	5.0231	450°—1 hr.	1.5404	3.4827	5.82	0.7567	2.8988	217.	261.
7	4.9715	600°—1 hr.	1.7019	3.2696	0.71	0.8468	3.2026	259.	264.

Sample calculation. Tube G. Original water content of gel, 34.7%. Loss on activation, 0.792 gm. This was associated with $\frac{65.3}{34.7}$ *of 0.792 = 1.49 gm. of active alumina. Amount sorbed per gram of active alumina is 0.3938/1.49 = 264 mgm.*

From this original gel sorbents having different amounts of water were prepared, as shown in the table. The solid line shows the saturation values per gram of "sorbent" plotted against the water content. Apparently measurements with two sorbents even from the *same original gel* are comparable only when the extent of dehydration is the same, if the results are expressed in this manner. Many comparisons made between different sorbents in the literature mean very little.

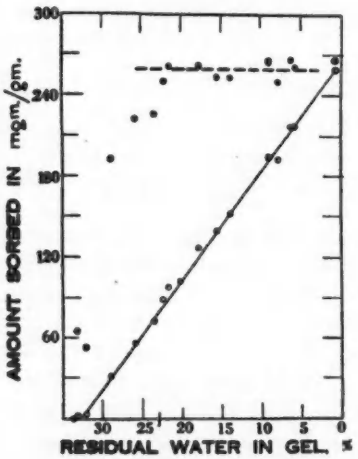

FIG. 1. *Sorption of benzene by alumina gels differing in residual water content. Solid line, sorption values as in mgm./gm. sorbent. Broken line, sorption values as mgm./gm. active alumina.*

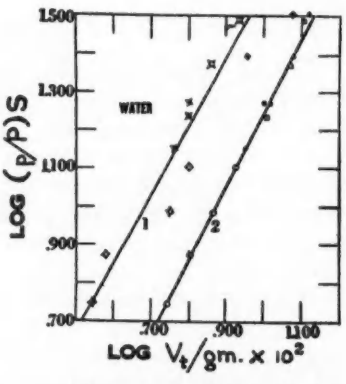

FIG. 2. *Sorption results for water plotted according to Patrick's equation. Curve 1, log (p/P)S against log. vol. of liquid sorbed/100 gm. sorbent. Curve 2, log (p/P)S against log. of liquid sorbed/100 gm. active alumina.*

It will be noted in Table I that only a very small amount of water was given off below 200° C. After the loss of a certain amount of water the sorption of benzene is approximately proportional to the extent of dehydration. This suggests that one of the important activation factors, although certainly not the only one, is the liberation of secondary valences of Al_2O_3, corresponding to additional surfaces or pore space for sorption. The sorption within certain limits depends on the amount of *active alumina*.

The sorbent consists of a certain amount of active alumina with more or less inert or unactivated gel, either original or modified, with probably some water in a new relation to the Al_2O_3. One might represent it as $x Al_2O_3 . (y Al_2O_3 . n H_2O) . z H_2O$, where $x Al_2O_3$ is the active part and the rest inert, or almost so. The amount of benzene taken up by one gram of "active alumina" calculated for sorbents having from 0.7 to 22% residual water approximates a constant value. This is shown in Table I, or by the broken line in Fig. 1. It means that results for gels of different water content can be put on a common basis.

In any series of sorption experiments, indeed in duplicate determinations, it is of advantage to be able to use tubes of both fresh and reactivated gel. The water content of these may vary somewhat, causing diverging values if expressed per gram of "sorbent". It has been found that results for ether obtained with gels of different water content approach a constant quantity when expressed as amounts per gram of active alumina (10).

Similar results are shown for water in Fig. 2, where they are plotted according to Patrick's equation (7). In Curve 1 the logarithm of the product of the partial pressure and surface tension of the liquid at the sorption temperature, $S(p/P)$, is shown plotted against the logarithm of the liquid volume at that temperature, V_l, per gram of sorbent. Much better agreement is observed in Curve 2, where $S(p/P)$ is plotted against the logarithm of V_l per gram of active alumina (V_l/gm.).

While obviously the method can not be rigorously applied to compare sorption by different types of gel, its value is demonstrated by the three examples above. The results for this paper are therefore expressed in this manner. For comparison with other work the general isotherm is expressed in both ways.

Experimental Results

The results for alumina at 80, 60, 50, and 40° C. and for partial pressures from 74.7 mm. to 147.5 mm. are given in Table II. The curves from the data at 40° C. are shown in Fig. 3. These are typical. The broken line is the total sorption line which the curve follows while the alumina is 100% efficient. The curves for the other temperatures, being very similar, are omitted to save space.

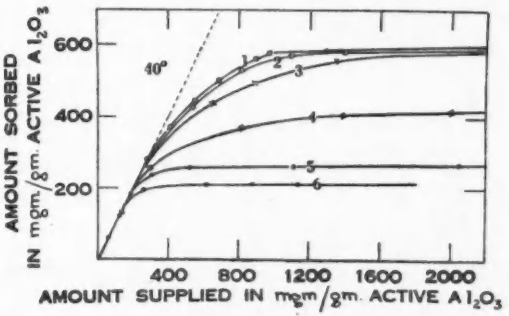

FIG. 3. *Typical sorption curves. Alumina at 40° C. Vapor pressures (mm.):—Curve 1, 178; Curve 2, 167; Curve 3, 147.5; Curve 4, 118.2; Curve 5, 94.7; Curve 6, 74.7.*

Curves 1 and 2 represent the results of experiments in which the vapor pressure was slightly lower than the saturation pressure. Such curves are characteristic. Though the total amount sorbed is not very different from that obtained at lower vapor pressures, the slope is steeper and saturation values are reached more abruptly. This was also noted in the case of water.

Fig. 4 shows the relative sorption

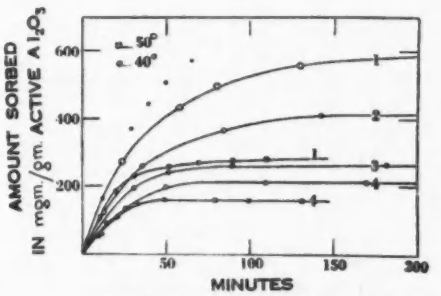

FIG. 4. *Relation between amount sorbed and time. Vapor pressures (mm.): Curve 1, 147.5; Curve 2, 118.0; Curve 3, 94.7; Curve 4, 74.7.*

TABLE II

SORPTION OF BENZENE BY ALUMINA

A	B	C	A	B	C	A	B	C	A	B	C
80° C.											
Tube 5.	*P.p., 147.5 mm.*		*Tube 5.*	*P.p., 118 mm.*		*Tube 6.*	*P.p., 94.7 mm.*		*Tube 6.*	*P.p., 74.7 mm.*	
176	132	11	125	109	10	59	56.5	6	53.6	50.1	7
353	145	22	250	123	20	154	100.8	16	123	89.8	16
546	145	34	374	124	30	256	103.4	26	191	91.3	25
			574	124	46	394	104	40	268	91.3	35
112	98	7									
225	135	14	123	108	10	49.3	48.5	5	61	58.4	8
353	145	22	222	123	18	118	97.6	12	161	90.5	21
514	145	32	320	125	26	217	103.4	22	421	91.1	55
			480	125	39	394	104	40	*	91.1	
			Tube 6.	*P.p., 118 mm.*		840	104	65			
			118	110							
			236	125							
			413	125							
60° C.											
Tube 3.	*P.p., 147.5 mm.*		*Tube 3.*	*P.p., 118.2 mm.*		*Tube 3.*	*P.p., 94.7 mm.*		*Tube 4.*	*P.p., 74.7 mm.*	
113.7	107.4	10	197	143.4	26	58.9	58.0	10.8	73.3	72.5	14
227.4	156.3	20	343	150	45	176.7	122.8	32.4	133	110.5	32
341	167.1	30	835	150	110	294.5	128.2	54	377	111.6	72
455	168.7	42				825	130.2	151	786	111.4	150
758	168.3	74	304	147	40	1179	129.2	216			
947	168.7	94	835	150	110	1355	129.2	248			
50° C.											
Tube 3.	*P.p., 147.5 mm.*		*Tube 3.*	*P.p., 118.2 mm.*		*Tube 3.*	*P.p., 94.7 mm.*		*Tube 3.*	*P.p., 74.7 mm.*	
105	104	11	120	121.4	16.5	94.1	91.9	18.6	51.7	49.3	10
190	178	20	259	204	36.8	294	167.6	58.0	113.7	110.6	22
305	221	32	435	206	62	470	169.7	93	176	143.1	34
495	250	52	961	208	132	706	169.0	133	258	154.8	50
667	262	70	1678	213	238	1059	169.3	193	414	153.8	80
857	267	90							682	153.8	132
1047	272	110	273	201	39						
1752	273	184	486	207	770				258	152.3	50
22381	272	250	911	209	130				517	154.3	100
			1480	210	211						
			2277	210	325						
			3188	209	455						
			3497	209							
			3796	210							
40° C.											
Tube 4.	*P.p., 178.5 mm.*		*Tube 4.*	*P.p., 167 mm.*		*P.p., 147.5 mm.*			*P.p., 118.2 mm.*		
192	185	14	127	122		133	129	12	127	125	13
411	369	30	280	273	12	1660	548	150	297	258	31
549	443	40	535	429	26	2770	558	250	815	369	85
686	503	50	815	532	48	3650	567	330	1392	407	145
892	565	65	1095	575	75	5310	574	480	1697	409	178
1097†	576	80	1401	578	101	5750	573	520	1870	420	
			1529	583	128				1970	437	
974	580		2802	583	242	267	273	24	2121	433	
1797	583					646	433	58	2970	433	
2620	591					891	497	80	4922	434	
						2785	572	251	*P.p., 94.7 mm.*		
						3890	572	350	87.9	87.8	15
						4467	572	401	187.5	192	32
									305	238	52
									528	258	90
									1067	264	182
									1407	265	240
									2051	266	350
									2638	267	450
									3225	268	550

NOTE:—A = *Amount of benzene supplied in mgm./gm. active* Al_2O_3. B = *Amount of benzene sorbed in mgm./gm. active* Al_2O_3. C = *Time in minutes. P.p. = Partial pressure.* **Counter stuck.* † *Thermostat slightly high—repeated.*

velocities for different concentrations at 40° C. Two curves for high and low concentrations of vapor at 50° C. are included for comparison.

Efficiency of the Alumina

Efficiency curves may be constructed from the sorption curves. In Fig. 5 the amount taken up per gram with 100% efficiency is related to the concentration of benzene in the vapor-air mixture and to the temperature of the sorbent. These efficiency curves are subject to a relatively large error in transposition from the original sorption curves. They do, however, furnish an approximate estimate of the efficiency for other temperatures and concentrations. They also show the decreasing efficiency with increasing temperature, which becomes more pronounced with high concentrations.

Isotherms

The saturation value for a sorption curve represents the amount of vapor held by the sorbent at a definite equilibrium pressure. Typical isotherms are obtained on plotting these values against the vapor pressure. These are shown in Fig. 6.

If the saturation values for all temperatures are plotted against the relative pressure (p/P), almost all the points fall on one curve, showing that the sorption depends on the ratio p/P and not on the temperature. This will be seen in Fig. 7, data for which are found in Table III. In Curve 1 the saturation values are given as mgm./gm. of sorbent; in Curve 2 as mgm./gm. of active alumina. The agreement is closer in Curve 2.

Owing to differences in the amount of air present at the same relative pressure of benzene for different temperatures, deviations from Trouton's general isotherm would be expected. All equilibrium values will be slightly lower than those obtained by a static method employing the pure vapor unmixed with air.

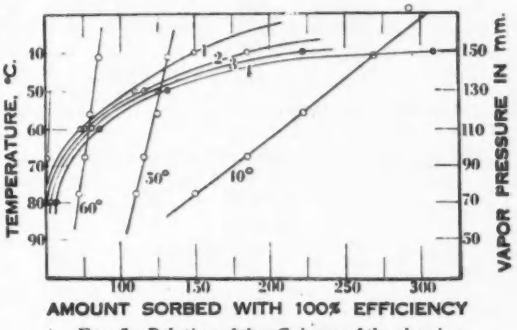

FIG. 5. *Relation of the efficiency of the alumina to temperature and concentration. Concentrations (by volume):—Curve 1, 9.83; Curve 2, 12.5; Curve 3, 15.5; Curve 4, 19.4.*

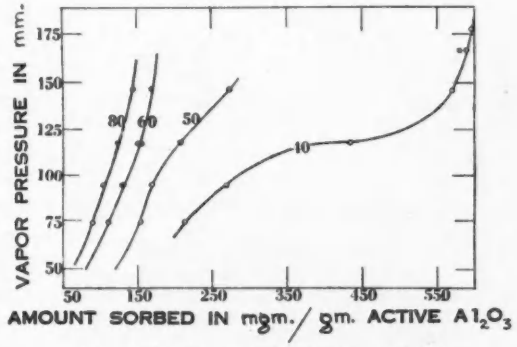

FIG. 6. *Isotherms for 80, 60, 50 and 40° C.*

TABLE III

EQUILIBRIUM VALUES FOR THE GENERAL ISOTHERM AND PATRICK'S EQUATION

Temp., °C.	p/P	Mgm./gm. sorbent	Mgm./gm. active Al_2O_3	V_s in cc./gm. Al_2O_3	$S(p/P)$	Cc. vapor (S.T.P.)/gm. active Al_2O_3
80	0.137	47.6	91.2	0.113	2.79	26.2
	.173	52.6	104.	.128	3.51	30.
	.216	68.2	125.	.153	4.38	35.
	.270	80.3	145.	.179	5.48	36.
60	.192	76.2	111.4	.137	4.23	32.0
	.244	110 and 104	129 and 130	.156	5.36	37.3
	.304	117	150	.184	6.70	44.
	.380	136	169	.202	8.36	48.
50	.278	107	154	.182	6.53	44.2
	.352	134	169	.200	8.27	48.6
	.439	165	212	.248	10.33	60.3
	.548	218	272	.321	12.9	78.1
40	.413	149	214	.251	10.61	61.4
	.523	213	268	.314	13.45	77
	.653	302	433	.509	—	124
	.815	498	572	.670	—	164
	.923	409	583	.683	—	170

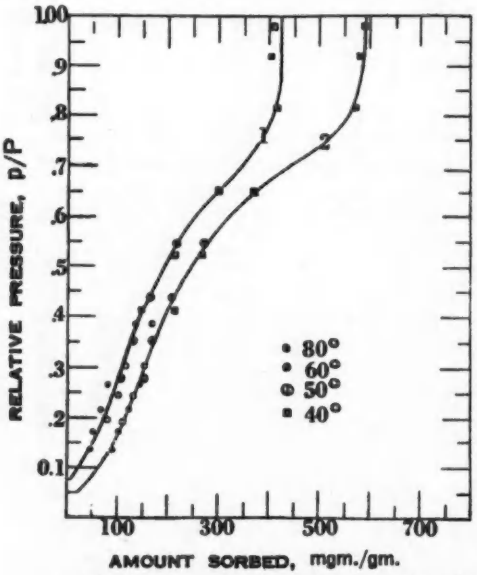

FIG. 7. *General isotherm showing relation of amount sorbed at different temperatures to relative pressure. Curve 1, amount sorbed in mgm./gm. sorbent. Curve 2, amount sorbed in mgm./gm. active alumina.*

When the logarithm of the vapor pressure is plotted against the logarithm of the amount sorbed, straight lines are obtained for the 80 and 60° C. isotherms. With the 50 and 40° C. isotherms, as the vapor pressure approaches the partial pressure of the liquid at the sorption temperature, the curves fall away from straight lines (Fig. 8).

The data for the quantities in Patrick's equation (7) are given in Columns 5 and 6 of Table III. The logarithmic curve in Fig. 8 approximates a line or lines for low partial pressures, but the agreement is not as good as with water.

The change in sorption potential shows that at high relative pressures capillary condensation predominates,

and yet Patrick's equation, derived for pure capillary condensation, does not apply to these very points.

Discussion

As has been pointed out, various hydrates of alumina are known to exist. If, in the case of water, the forces which produce hydration are operative during or immediately after adsorption, one would expect that differences might appear in the general isotherms for water and benzene. These are given in Fig. 9, data for which will be found in Tables III and IV. Equilibrium values are expressed as cubic centimetres of liquid at the temperature of the sorbent in curves marked "1", and as cubic centimetres of vapor reduced to S.T.P., in curves marked "2".

It will be noted that the curves differ considerably. The gel at saturation contains water in greater volume than benzene. It is perhaps surprising to find, however, that, except near saturation, the alumina holds a greater volume of liquid benzene for a given relative pressure. When the vapor pressure is two-thirds of the saturation pressure, the gel has taken up only one-fifth of the saturation amount of water, whereas three-

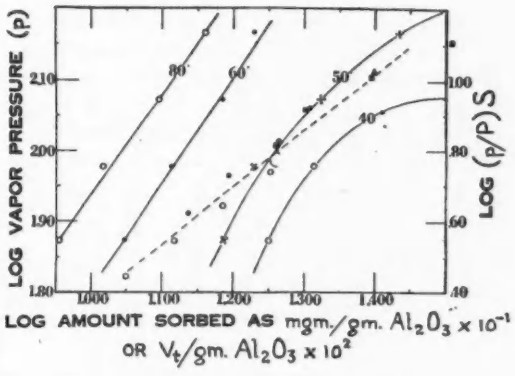

FIG. 8. *Logarithmic curves for* $\frac{x}{m} = K.P.^{\frac{1}{n}}$ *and Patrick's equation. Solid lines, log. vapor pressure against log. mgm./gm. alumina* $\times 10^{-1}$. *Broken line Patrick's equation against log* $(p/P)S$ *against log.* V_t*/gm. alumina* $\times 10^2$.

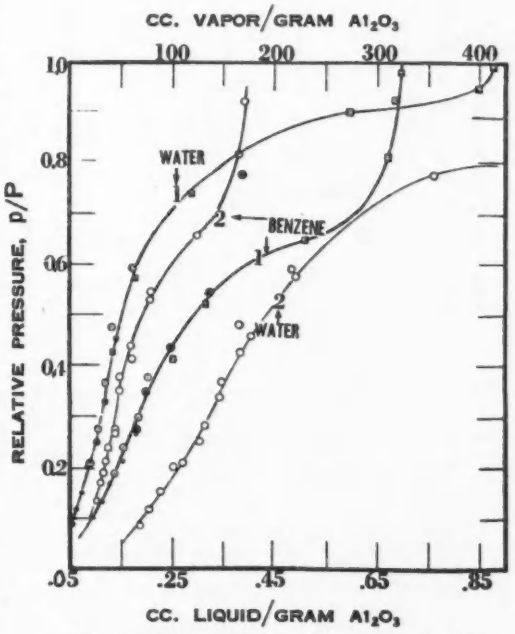

FIG. 9. *Sorption of water and benzene on alumina —comparison of general isotherms. Curve 1, cc. liquid/100 gm. alumina. Curve 2, cc. vapor/gm. alumina.*

TABLE IV

EQUILIBRIUM VALUES FOR WATER

Temp., °C.	p/P	Vapor cc./gm. Al_2O_3	V_l in cc./gm. Al_2O_3	Temp., °C.	p/P	Vapor cc./gm. Al_2O_3	V_l in cc./gm. Al_2O_3
80	0.089	66.9	0.056	50	0.255	127	0.103
	.118	77.9	.064		.339	146	.118
	.151	89.2	.074		.456	176	.143
	.203	102.	.085		.595	214	.174
					.776	477	.386
60	.211	111.	.090	40	.428	167	.135
	.280	137.	.105		.572	220	.178
	.369	148.	.120		.768	355	.287
	.479	162.	.132		.900	770	.596

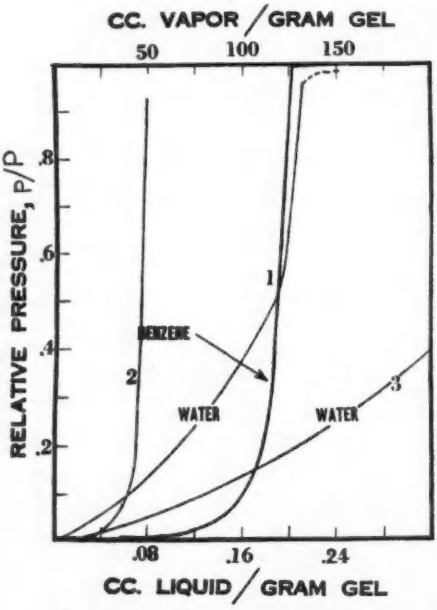

FIG. 10. *Sorption of water and benzene on silica gel—comparison of general isotherms (from Lambert and Foster (5)). Curve 1, Lambert and Foster's curves for benzene and water (Graph V) expressed as cc. liquid/gm. gel. Curves 2 and 3, same results for benzene and water expressed as cc. vapor (S.T.P.)/gm. gel.*

fourths of the total quantity of benzene is held at this relative pressure. One might expect the positions to be reversed if the "chemical" or hydration forces played any part in adsorption.

When x/m is expressed as cubic centimetres of vapor at S.T.P. a comparison is obtained of the *relative number of vapor molecules* taken up. It will be seen from the curves marked "2" that the numbers of molecules of water sorbed exceeds that of benzene over the whole range of partial pressures investigated.

Recently Lambert and Foster (5) reported very similar results for the sorption of these vapors by silica gel. The data estimated from the initial part of the curves are plotted in Fig. 10. The notations are the same as in Fig. 9.

In a discussion of their results Foster states (3) "When the gel is *half* saturated with water the pressure is $\frac{1}{5}$ of the saturation pressure, as compared with $\frac{1}{30}$ of the saturation pressure for benzene. The forces tending to cause layer adsorption must be weaker for water than for benzene, while the cohesive forces are of the same order of magnitude."

It will be noted however that, if the amounts are calculated in cubic centimetres of vapor, the number of molecules held is practically the same at low relative pressures (0.01–0.04, Curves 2 and 3). These low pressures probably represent true adsorption. Beyond a relative pressure of 0.04 the number of molecules of water taken up by the alumina greatly exceeds the number of molecules of benzene sorbed.

McBain records (6) that with a certain charcoal almost all of the large amount of water sorbed was taken up at a relative pressure of 0.3. With toluene a large percentage of the total amount sorbed was taken up at vapor pressures of a few hundredths of the saturation pressure. Again, the final saturation values for water exceeded those for toluene and other organic solvents, as in the present investigation.

Apparently the larger capacity of alumina for water vapor does not point to the action of hydration forces but rather to the relative size of the water molecule and its polar nature. Again, Milligan (9) reports that the X-ray pattern of the alumina does not change during sorption. There seems, then, to be little necessity for the assumption that hydration or any special "chemical" forces play any marked role in the sorption of water by alumina.

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TESTS FOR MESOTHORIUM IN RADIUM FROM LABINE POINT, GREAT BEAR LAKE[1]

By G. C. Laurence[2] and F. B. Friend

Abstract

A sample containing 50 mgm. of radium bromide, prepared from ore obtained from the Echo Bay deposits in Canada, was tested for mesothorium impurity by the gamma ray absorption method. The material was found to be free from mesothorium within the limits of the experimental error, 0.2% radiation equivalent.

As a confirmatory test a number of samples of the ore were analyzed for thorium in the National Research Laboratories, Ottawa. Quantities of thorium up to 0.07% of the uranium content were found, indicating a possible mesothorium impurity in the finished radium of 0.021% radiation equivalent.

Introduction

In appraising the pitchblende deposits on Great Bear Lake, an important consideration is the possibility of mesothorium in the ore. This isotope of radium is an objectionable impurity because it decays by 10% per year. The purchaser of radium naturally insists that it be practically free from this short lived source of radiation.

Mesothorium is a member of the thorium series and exists in old minerals in concentrations of one part in 2.5 thousand million parts of thorium present. Ore containing one part thorium to 100 parts uranium will yield radium containing a mesothorium impurity of 0.0011% by mass. This corresponds to 0.27% by radiation equivalent, since mesothorium radiates 240 times more strongly than radium.

The impurity of radium is frequently quoted in percentage by mass. The purchaser pays for radiation equivalent and therefore is interested in impurity measured in percentage of radiation equivalent. Care is necessary to avoid confusing these methods of rating impurity when making comparison between ores.

Analyses of the ore showing important mineralogical constituents have been published by Spence (2) and Traill (3) of the Dominion Government Department of Mines. These authors have recorded no thorium in the ore. However, small quantities of radioactive impurities were unimportant in their work, and a special search was not made for them.

Test for Mesothorium in Finished Radium

A physical test for mesothorium in the finished radium bromide extracted from this ore has just been completed in this laboratory. Bothe's (1) method was adopted with some modification, permitting the use of a differential method of measurement and a consequent gain in accuracy. The method makes use of the difference in the coefficients of gamma ray absorption in lead between radium ($\mu = 0.50$ cm.$^{-1}$) and mesothorium ($\mu = 0.62$ cm.$^{-1}$). A

[1] *Manuscript received March 8, 1934.*
Contribution from the National Research Laboratories, Ottawa, Canada.
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preparation containing a fraction η of mesothorium shows an apparent increase in absorption coefficient of η (0.62 cm.$^{-1}$ — 0.50 cm.$^{-1}$) in comparison with radium.

Comparison was made of the radiation from approximately equal quantities of radium recently prepared from the Echo Bay ore and radium* known to be practically free from mesothorium. The radiation from the two differed in intensity by a small amount ΔI_1 when measured through a filtration of 1 cm. of lead, and ΔI_6 when measured through 6 cm. of lead. Ignoring second order differences,

$$5 \text{ cm. } \eta\ (0.62\text{–}0.50) \text{ cm.}^{-1} = \Delta I_6 - \Delta I_1.$$

ΔI_1 and ΔI_6 were observed as shifts in the instrument reading when one sample was quickly replaced by the other. This was accomplished by mounting the two preparations on opposite ends of an arm free to rotate about its centre. Suitably rigid construction and spring catches ensured that the radium samples always returned to the same position. The readings of the instruments were calibrated readily in percentage of the intensity by adding a small known amount of radium.

The ionization chamber was a cubical aluminium box of 18 cm. edge having a central electrode leading to the grid of an electrometer valve which indicated the changes in the ionization current. Direct current valve amplification and a low period milliammeter were used. Suitable grid bias potential and a shunt circuit for a milliammeter in the plate circuit compensated for the effect of the average ionization current so that the instrument indicated the small changes ΔI_1 and ΔI_6 directly.

About 1500 readings of ΔI_1 and ΔI_6 were taken with an equal number of "zero" readings. Corrections were applied to ΔI_1 and ΔI_6 to take into consideration the absorption in the sources themselves which happened to be of different thickness. These amounted to $0.0035 \pm 0.0001\ I_1$ and $0.0020 \pm 0.0001\ I_6$ respectively. The possible inaccuracy in computing these corrections will introduce an error of less than 0.04% in the result.

An advantage of the method is that most instrumental sources of error are eliminated by compensation. The seriousness of the others is easily gauged by experimentally increasing their causes. An uncertainty of 0.1% in the result is due to the difficulty of mounting the two preparations, which were of different shape, at the same average height. The error in the result due to all causes, including the small random fluctuations in the readings, is less than 0.2%. Table I shows the values obtained for $\Delta I_6 - \Delta I_1$.

TABLE I

VALUES OBTAINED FOR $\Delta I_6 - \Delta I_1$

$\Delta I_6 - \Delta I_1$, %	No. of readings on which value is based	Weight
+0.04	600	$\sqrt{2}$
−0.07	300	1
−0.11	300	1
+0.06	300	1

* *The Canadian Standards which were conditioned from two tubes of pure radium chloride prepared from Katanga ore in 1924. One of these has been accepted by the International Radium Commission as Substandard XIII.*

The weighted mean is -0.1%. The corresponding value of η, the mesothorium impurity is -0.02%, a value well within the limits of experimental error $\pm 0.2\%$. Therefore the mesothorium impurity in the sample of LaBine Point radium does not exceed 0.2% by radiation equivalent. This corresponds to less than 0.0008% by mass.

Thorium Content of the Ore

These results have been confirmed by analyses of the ore for thorium. Four samples were tested in the National Research Laboratories, with the following results:—

Sample 1, of silica type ore*, from No. 2 pit, No. 2 vein, was found to contain 0.045% ThO_2 and 61.4% U_3O_8.

Sample 2, of silica type ore, a composite from No. 1 pit, No. 1 vein, and No. 1 pit, No. 2 vein, contained 0.027% ThO_2 and 57.2% U_3O_8.

Sample 3, of carbonate type ore, from No. 9 pit, No. 2 vein, contained 0.02% ThO_2 and 54.2% U_3O_8.

These three samples were kindly provided by Mr. Spence of the Department of Mines. They had been in his possession for some time before the question of mesothorium impurity had arisen, and therefore may be considered as chosen at random.

Sample 4 was a roasted and milled carbonate type of ore obtained from underground working of the 1200 ft. section, No. 9 to No. 12 pit, No. 2 vein. It was found to contain 0.01% ThO_2 and 30.8% U_3O_8.†

It is calculated from the thorium-uranium ratio of these samples that they would yield finished radium having the following amounts of mesothorium impurity.

TABLE II

Sample no.	Mesothorium impurity, %		Sample no.	Mesothorium impurity, %	
	By radiation equivalent	By mass		By radiation equivalent	By mass
1	0.021	0.00009	3	0.010	0.00004
2	0.013	0.00005	4	0.009	0.00004

Conclusion

The mesothorium impurity in LaBine Point radium, as shown in these investigations, is far too small to be of any practical importance or meet with objection from the most fastidious market.

Acknowledgment

The thanks of the writers are due Mr. C. W. Davis of these laboratories for analyzing a number of samples of the ore for thorium content.

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* *See References (2) and (3) for description of ore and veins.*

† *Sample No. 4 was supplied through the courtesy of Eldorado Gold Mines, Ltd., who also kindly lent this laboratory two radium bromide preparations of 17 and 25 mgm. for the physical tests.*

THE THEORY OF OPTICAL ABSORPTION IN ALKALI METAL CRYSTALS[1]

By W. H. Watson[2]

Abstract

The experimental results of R. W. Wood are compared with theory using the model of free electrons perturbed by the periodic lattice potential. All relevant data are collected in a table in which it is seen that in sodium, potassium, rubidium and caesium the wave-length of the upper limit of the absorption band in the visible and near ultra-violet is proportional to the square of the lattice constant, while lithium occupies an anomalous position. The facts at present available do not permit a completely definite test of the absolute values of these wave-lengths given by the theory.

Introduction

In the Sommerfeld theory of metals, an electron gas is pictured as moving in the field-free space inside a potential wall. With the aid of certain assumptions regarding the variation of electric potential at the surface of the metal it is possible to give an adequate account of the thermionic emission of electrons from metals. When, however, one attempts to explain the photoelectric effect by means of the same model one finds, as Tamm and Schubin (18) have shown, that there is no mechanism to account for conservation of energy and momentum in individual absorption processes in the body of the metal. The most obvious improvement of model which will remove this difficulty, is made by introducing the periodic variations of potential which must exist in the metal lattice, and by calculating the motion of electrons in this three-dimensional periodic field. This problem has been investigated in the general case, according to the perturbation methods of quantum mechanics by Bloch (1), Morse (10), Peierls (13), Wilson (19), Kronig (5, 6), and in a special one-dimensional case by Strutt (17), Kronig and Penney (9) and by Hill (4). However, even although we have complete spectroscopic knowledge of the atoms which make up the crystal and an accurate model of the crystal structure, in no case of an actual crystal has the exact solution been worked out, nor does it appear to be attainable, on account of the complexity of the calculations.

The most striking result of these new theoretical inquiries consists in this, that the energy levels which can be occupied by electrons moving in any particular direction in the crystal are grouped into bands separated by intervals of disallowed energy values. These regions of disallowed energies occur in the neighborhood of the energy values corresponding to which, for the direction in question, selective reflection of the electrons takes place at successive systems of net planes in the crystal. On account of this distribution of allowed energy levels it follows that the optical absorption spectrum of the metal in the visible and ultra-violet may be made up of alternating

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bands of high and low absorption, and that on the short-wave side of an X-ray absorption edge due to solid metal there should occur fluctuations in the coefficient of absorption extending in the spectrum over some hundreds of volts, which depend on the crystal structure of the metal and are not present in the atomic absorption by the same element in a vapor or gas (7).

Absorption bands in the ultra-violet have been known experimentally for a long time in the case of silver, copper and gold and have received theoretical comment in the light of the above ideas from Fröhlich (2) while the transmission band in silver has been discussed by Schubin (14)*. More recently R. W. Wood (20) has observed that thin films of the alkali metals deposited on quartz at low temperatures are transparent over regions extending from 1860 Å to 2050, 2100, 3150, 3600, and 4400 Å in the five metals lithium, sodium, potassium, rubidium and caesium. He has also shown that this high transparency is accompanied by a low reflecting power.

In this paper the writer has brought together selected data on the alkali metals for the purpose of comparing the facts described by Wood with the theory referred to above. The connection between the theory and Wood's observations has been already indicated by Kronig (8).

We consider the motion of electrons in a cubical box of side Ga where G is an integer and a is the length of the elementary cubic cell of the lattice. In a steady state the equation for electron wave functions independent of the time is

$$\Delta\Psi + \frac{8\pi^2 m}{h^2}(W-V)\Psi = 0 \qquad (1)$$

where W is the energy, and $V(x, y, z)$ is the potential energy of the field in which the electron moves. The null value of the energy is so chosen that the mean value of V vanishes. In the case of the alkali metals the lattice is body-centered cubic so $V(x, y, z)$ must have the form

$$V(x, y, z) = \Sigma F(x-n_1 a, y-n_2 a, z-n_3 a) + \Sigma F(x-(n_1-\tfrac{1}{2})a, y-(n_2-\tfrac{1}{2})a, z-(n_3-\tfrac{1}{2})a)$$

summed over all n_1, n_2, n_3 less than G. If we express V in a Fourier series we have

$$V(x, y, z) = \Sigma v(k) e^{\frac{2\pi i}{a}(k.r)} + \Sigma v(k) e^{\frac{2\pi i}{a}(k.r')}$$

where k stands for the triplet of values k_1, k_2, k_3,

$$(k \,.\, r) = k_1 x + k_2 y + k_3 z \,, \qquad (k \,.\, r') = k_1 (x-\tfrac{1}{2}a) + k_2 (y-\tfrac{1}{2}a) + k_3 (z-\tfrac{1}{2}a) \,,$$

and summation is over all triplets (k_1, k_2, k_3) where these are positive or negative integers or zero. Hence

$$V(x, y, z) = \Sigma v(k) e^{\frac{2\pi i}{a}(k.r)} \left(1 + e^{-\pi i(k_1+k_2+k_3)}\right)$$

If $(k_1 + k_2 + k_3)$ is an even number

$$V = \Sigma 2v(k)\, e^{\frac{2\pi i}{a}(k.r)} \qquad (2)$$

* *Note added March, 7 1934: An important contribution to the experimental study of the optical properties of thin films of silver, copper and gold and other metals has been made by A. Smakula (Z. Physik, 86, 3-4, p. 185, 1933; Physik. Z. 34, p. 788, 1933). Schubin's conclusions are not confirmed.*

and if $(k_1+k_2+k_3)$ is odd the contribution to V vanishes. So we may use Equation (2) to represent V with the condition that $(k_1+k_2+k_3)$ is even.

We require a solution of Equation (1) which satisfies the given boundary condition that the waves are contained in a cube of side Ga. According to Bloch (1) this has the form

$$\Psi_{l_1 l_2 l_3}(x, y, z) = u_{l_1 l_2 l_3}(x, y, z)\, e^{2\pi i (l_1 x + l_2 y + l_3 z)/Ga} \tag{3}$$

where u is a function which like $V(x, y, z)$ has the period a parallel to the three axes of co-ordinates; l_1, l_2, l_3 can assume all integral values positive or negative and zero. They differ in different states of the motion and can be regarded as quantum numbers. For free electrons $u(x, y, z)$ is constant, and for strongly bound electrons its behavior in the neighborhood of a point in the lattice where there is an atom is the same as the Schrödinger function for the isolated atom. The corresponding energies are given in the case of free electrons by

$$W = \frac{h^2}{8\pi^2 m a^2 G^2}(l_1^2+l_2^2+l_3^2) = \frac{h^2}{8\pi^2 m a^2}(\xi^2+\eta^2+\zeta^2), \quad \xi = \frac{l_1}{G} \text{ etc.} \tag{4}$$

and in the case of the strongly bound electrons in "zero" approximation, by the energy levels of the isolated atoms. The effect of the periodic field of the lattice regarded as a perturbation is to split each non-degenerate atomic level into $2G^3$ levels (body-centered cube); it is essential for the validity of this method that the energy breadth of this group of levels should be small compared with the interval between neighboring atomic levels. In the limit when G tends to infinity, the effect of the perturbation on the free electron model is to divide (ξ, η, ζ) space into zones within any one of which the energy is a continuous function of ξ, η, ζ; on the other hand W suffers a discontinuous change when we pass from one zone to an adjacent one. Each zone contains $2G^3$ levels.

On the quite general ground of the strong electropositive nature of the alkali metals one expects that the free electron model is the correct one from which to start. There is however more definite quantitative evidence in favor of this model. In the first place, the form of the characteristic soft X-ray spectrum from solid lithium agrees very well with that calculated from the Sommerfeld model (12), whereas in beryllium and other metals with two or more conduction electrons per atom such is not the case (16). Secondly, the electrical conductivities of the alkali metals calculated on the assumption of free electrons are of the correct order of magnitude whereas those of copper, silver and gold differ by at least a factor 10 from the experimental values. Thirdly, Fröhlich (2) has shown that the optical absorption of the alkali metals conforms well with the assumption of free electrons whereas that of silver, copper and gold does not. The essence of his argument is that if n is the refractive index for light of frequency ν, and k is the absorption coefficient

$$nk\nu^2 = K + \frac{e^2}{4\pi m^2}\rho(\nu)\,|p(\nu)|^2 \tag{5}$$

where K arises from continuous absorption (3) while the second term has a non-zero value only in an absorption band, $\rho(\nu)$ being the density of electrons in the initial state, and for free electrons $|p(\nu)|^2$ is small compared with h^2/a^2. In the absorption bands of Ag and Au this condition is not fulfilled while, in the case of the alkali metals, the scanty data available seem to show that it is. Finally there is the transparency observed by Wood which we shall find fits reasonably well with the perturbed free electron model. Before we discuss this, it is not out of place to point out the importance of optical investigation of the complete series of the alkali metals in connection with the theory of electron motion in crystals. On account of the looseness of electron binding to these metals all energies associated with electron transition in an alkali metal crystal are smaller than the corresponding energies in any other metals and this means that the interesting optical properties are brought into a region of the spectrum where the technical difficulties of observation are less serious, caesium, of course, being the most favorable case. Through the series of alkali metals the lattice constant varies from 3.5 Å to 6.1 Å; this allows a good test of the theory relating optical levels with the size of the lattice cell. Finally, from the point of view of refining the theory, simple electrical models of the alkali atoms can be made so as to allow calculation of the important terms in the Fourier series which represents the periodic potential in the lattice. It must be the aim of any theory of the properties of crystals to join together the evidence from absorption and the emission spectra in the far ultra-violet. The alkali metals offer the best hope of achieving this.

The energy discontinuities, which are introduced when we consider the perturbation of the free electron motion by the lattice field, arise in the second approximation from the removal of the degeneracy which exists for states lying adjacent to the common boundary of two zones in (ξ, η, ζ) space. Kronig (5, 6) has shown that if α, β, γ are any integers then the transition from a state ξ, η, ζ to one ξ', η', ζ' is governed by the selection rule

$$\xi' = \xi \pm 2\pi\alpha, \qquad \eta' = \eta \pm 2\pi\beta, \qquad \zeta' = \zeta \pm 2\pi\gamma \tag{6}$$

in the case of a simple cubic crystal. It is readily seen that in the case of a body-centered cube α, β, γ are restricted by the condition that $\alpha+\beta+\gamma$ is an even number. The most frequent transitions occur for the smallest possible values of α, β, γ. The equation of the boundary in (ξ, η, ζ) space between two zones is

$$\xi'^2 + \eta'^2 + \zeta'^2 = \xi^2 + \eta^2 + \zeta^2 \tag{7}$$

Thus the set of values (α, β, γ) determines a plane in (ξ, η, ζ) space, namely, the locus of states (ξ, η, ζ) whose corresponding electron wave is selectively reflected by the system of net planes in the lattice normal to the direction (α, β, γ). Light is absorbed or emitted only when an electron is transferred from one zone to another.

In our free electron model all those states are occupied for which

$$W(\xi, \eta, \zeta) = \frac{h^2}{8\pi^2 ma^2}(\xi^2 + \eta^2 + \zeta^2) \leq W_i \tag{8}$$

where W_i is the top of the Fermi-Sommerfeld distribution. The smallest light energy which is absorbed by the crystal at $0°K$ is

$$W(\xi-2\pi, \eta-2\pi, \zeta) - W(\xi, \eta, \zeta) \tag{9}$$

where the state (ξ, η, ζ) has the energy W_i. This corresponds to the fact emphasized by Fröhlich (2) that the lower frequency edge of the first absorption band of a crystal corresponds to transitions from the highest possessed energy levels of one zone to the lowest (empty) levels of the next. In this absorption band the highest energy which can be absorbed is given by Equation (9) when (ξ, η, ζ) corresponds to the lowest energy of the Fermi distribution. Now, in actual practice, since there is only one state of zero energy, the frequency for which absorption passes into transparency will correspond to an initial state not exactly at the bottom of the Fermi distribution and will depend on the criterion adopted for determining the high frequency edge of the absorption band. On the other hand by examining the course of the absorption curve in the transition region we should be able to calculate the actual energy limit for the second zone. Experiments are now in progress in this laboratory to investigate this in the case of caesium.

Numerical Facts

Wood's experiments were carried out on films of the order of 500 atoms thick but the crystal structure of such layers should be reasonably independent of the surface on which they are deposited. The writer therefore feels justified in using the data for the solid metal. In Table I all energies are

TABLE I

PHYSICAL CONSTANTS OF CRYSTALS AND ATOMS OF ALKALI METALS

Element	Atomic no.	Density at 20° C. (gm./cc.)	Atomic weight (A)	No. of atoms per cc. $n \times 10^{-n}$	$a = \left(\frac{2}{n}\right)^{\frac{1}{3}}$ Å	a (obs.) Å	W_i	Ionization potential	$3^2S_{\frac{1}{2}} - 3^2P_{\frac{1}{2},\frac{3}{2}}$	$3^2S_{\frac{1}{2}} - 4^2P_{\frac{1}{2},\frac{3}{2}}$	Transparency limit $\left(\frac{L}{W_0}\right)$	$W_0 = \frac{h^2}{2ma^2}$	$\frac{L}{W_0}$
Li	3	0.53	6.94	4.59	3.51	3.46	4.65	5.36	1.84	3.82	6.03	12.07	0.500
Na	11	0.97	23.0	2.54	4.28	4.24	3.13	5.12	2.10	3.74	5.88	8.13	0.724
K	19	0.86	39.1	1.323	5.32	5.33	2.026	4.32	1.60 1.61	3.05	3.82	5.27	0.747
Rb	37	1.53	85.45	1.078	5.69	5.62	1.766	4.16	1.55 1.58	2.94	3.43	4.59	0.726
Cs	55	1.90	132.8	0.861	6.13	6.03	1.521	3.88	1.38 1.45	2.69 2.71	2.81	3.95	0.711

expressed in equivalent electron volts. The data in Columns 3 and 4 are taken from the International Critical Tables (I. 140) and from them n, the number of atoms per cc. (Column 5), and a (Column 6), the lattice constant in Å, are calculated by the formulas

$$n = \rho/Am_H, \quad a^3 = 2/n \tag{10}$$

where m_H is the mass of the hydrogen atom. In Column 7 are given the experimental values of a taken from Neuburger's (11) recent critical table of crystal data. With the exception of potassium the values are given for 100° K. In the subsequent calculations the values of a in Column 6 have been used. W_i is entered in Column 8 and calculated as follows:

$$W_i = \frac{h^2}{2m}\left(\frac{3n}{8\pi}\right)^{\frac{2}{3}} \qquad \text{(one free electron per atom).}$$

$$= \frac{h^2}{2ma^2}\left(\frac{3}{4\pi}\right)^{\frac{2}{3}}$$

In Columns 9, 10 and 11 are given respectively the ionization potential and first two members of the principal series of the optical spectra of these elements expressed in volts. The upper energy of the absorption band observed by Wood is shown in Column 12 and in Column 13 the value of

$$W_0 = h^2/2ma^2 \tag{12}$$

Column 14 shows the ratio of values in Column 12 to those in Column 13. It is strikingly evident that the ratio is sensibly the same for sodium, potassium, rubidium and caesium but is quite different for lithium. It may be that this difference in the behavior of lithium is to be correlated with the fact that, whereas in the other alkali metals W_i is less than the energy of the second member of the principal series (Column 11), in the case of lithium W_i is greater.

Using Equations (9) and (4) we obtain in the first approximation, for the upper limit of the absorption band (that is, the energy difference between the bottom of the Fermi distribution and the top of the second allowed zone)

$$W(2\pi, 2\pi, 0) = 2W_0 \tag{13}$$

In the second approximation we have to subtract from this the half-breadth of the forbidden band (6) which is given by $2v$ (200), the second coefficient in the Fourier series (1). We can obtain a lower limit for this from Wood's observations on caesium which transmits from 4400 to 1860 Å(*i.e.*, from 2.81 to 6.65 volts) and according to Wood appears to become less transparent at the upper limit. This gives a difference of 3.84 volts and therefore a lower limit for $2v$ (200) = 1.92 volts = 0.485 W_0. Hence we have the value 1.515 W_0 to compare with Wood's observation of 0.711 W_0. The value of the upper limit of the absorption band for the initial state (ξ_1, η_1, ζ_1) is

$$W'(2\pi, 2\pi, 0) = \frac{W_0}{4\pi^2}\left\{(2\pi-\xi_1)^2 + (2\pi-\eta_1)^2 + \zeta_1^2 - (\xi_1^2+\eta_1^2+\zeta_1^2)\right\} = 2W_0 - \frac{W_0(\xi_1+\eta_1)}{\pi} \tag{14}$$

The energy of the initial state is a minimum for $\xi_1 = \eta_1$ and if the second term of the right-hand member of Equation (14) is to account for $0.8\ W_o$ (1.515–0.711)

$$\frac{\xi_1}{\pi} = \frac{\eta_1}{\pi} = 0.4$$

and

$$W_1 = 0.08\ W_o \sim 0.2\ W_i$$

since

$$W_i = 0.385\ W_o\ .$$

The corresponding ordinate in the Fermi distribution curve is two-fifths of the maximum ordinate. The correction to $W\ (2\pi, 2\pi, 0)$ required in this way to bring the theory into agreement with Wood's observations thus seems too large. Experiments are necessary to remove doubt on this point, and also to determine the breadth of the transparent region by extending observations into the ultra-violet.

Lithium offers another problem. Here the theory in its simple form appears to fail, but as Wood (20, p. 354) has expressed doubt concerning the position of the lithium limit, perhaps the point should not be pressed at present. Nevertheless it is interesting to point out that the value given by Wood is very close to the first radiation potential observed in the soft X-ray emission spectrum of lithium by Skinner (15) who worked with the metal at a temperature supposedly sufficiently high (150° C.) to remove the regularity of the lattice and therefore all evidence of the lattice level scheme.

In conclusion it may be said that while the present experimental facts are insufficient to give a definite decision, the prediction of the theory regarding the dependence of the upper limit of the absorption band in sodium, potassium, rubidium and caesium on the lattice constant is verified, and a rough approximation is obtained to the actual values of these limits.

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VARIABLE PERSONAL EQUATION OF BISECTION IN PRIMARY TRIANGULATION[1]

By J. L. Rannie[2] and W. M. Dennis[3]

Abstract

The investigation demonstrates that errors of appreciable magnitude may occur in the measurement of angles of primary triangulation by certain observers, owing to variable personal equation of bisection. A simple method of eliminating these errors is described.

Introduction

In many branches of scientific practice it is a well understood fact that various observers have different personal equations of bisection of objects, *i.e.*, one observer may consistently point to the left of the centre while another may point as consistently to the right. It is also well known in observatory practice that the same observer may have different personal equations of bisection on stars of different magnitudes. Observing practices are designed to eliminate personal equation as far as possible, and the test of a good observer is not that he have a small personal equation but that he be consistent in whatever personal equation he possesses.

Application to Triangulation

In the measurement of primary triangulation angles it is taken for granted that the personal equation of bisection is practically the same for all objects sighted on, the angle being assumed to be free from error due to variable personal equation; at least it is considered that any residual error is smaller than the error of the angular measurements due to other causes and is not worth eliminating. This probably is nearly true in the case of most observers, as the years of successful triangulation testify, though in any case, if there is any variable personal equation, an error is introduced into the measurement of angles which might better be removed if it involves no more work—as it does not.

Variable Personal Equation

Occasionally, however, it is found that a very consistent observer has a very different personal equation when pointing, say, on signal lights of different size or intensity. In the case of such an observer the angular measurements may be quite appreciably in error, and the observer himself, or lateral refraction, or atmospherics, or theodolites are likely to receive blame which they do not deserve.

Elimination

While investigating the source of certain discrepancies in angular measurements by different observers on the staff of the Geodetic Survey of Canada,

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Department of the Interior, a case of decided variable personal equation on different lights was discovered in one officer who otherwise was proved to be a most consistent observer. Remedial measures were essential in his case, and it is believed worth while to apply the same remedy to all observers on the ground that even a small source of error which can be easily removed is worth while removing. The remedy consists in fitting a simple reversing prism on the eyepiece end of the telescope and taking half of the observations with the image direct and the other half with the image reversed horizontally —the same method as is employed in all observatories.

Tests of Personal Equation

The apparatus by which the effect was first recognized was simple. Two artificial stars were set up in a dark room about 100 ft. from a solidly mounted theodolite. The star in each case consisted of a very fine hole of nearly 0.01 in. diameter in a thin plate with a small electric lamp behind it, a rheostat being employed to regulate the intensity of the light. A program of measurement of the angle between the two stars was arranged with different intensities of the stars, care being taken in the arrangement of the program to eliminate the effect of any gradual change in the position of the stars.

Test Results

The observer mentioned above as having a different personal equation on different lights made the following typical measurements of the angle between the two stars. In the theodolites used the star or light image is centered between two parallel or slightly converging cross wires. Each of the results is the mean of eight measurements, four clockwise with telescope "direct" and four anticlockwise with telescope "reverse".

TABLE I

ANGLE BETWEEN TWO ARTIFICIAL STARS

Both stars fine and dim	Left star dim, right star bright	Difference	Both stars fine and dim	Left star bright, right star dim	Difference
4° 38′ 39″.88	4° 38′ 40″.20	−0″.32	4° 39′ 55″.28	4° 39′ 53″.58	+1″.70
39″.90	40″.55	−0″.65	54″.80	53″.88	+0″.92
4° 39′ 56″.25	4° 39′ 57″.12	−0″.87	55″.40	54″.72	+0″.68
56″.25	57″.12	−0″.87	55″.70	54″.55	+1″.15
			54″.95	54″.28	+0″.67
			55″.08	54″.35	+0″.73

It is evident from Table I that this observer placed the cross hairs farther to the right with reference to the bright star than he did with reference to the small dim star, the difference being over $\frac{3}{4}''$ of arc on the average. In other words had he had the same conditions in the field his measurement of the angle would have been almost one second too great or too small.

In order to separate his personal equations of pointing between fine dim and large bright lights, a right angled prism was fitted on the eyepiece end

of the telescope whereby the image was reversed horizontally; a number of pointings and circle readings were made alternately on a light when it was dim and bright, followed by the same number of pointings on the same light when it was dim and bright with the prism removed. Table II shows a sample of the readings taken by this observer.

TABLE II
DETERMINATION OF PERSONAL EQUATION

	Prism on; image reversed	Prism off; image direct	Difference	Mean
Large bright light— Mean of 10 single pointings	48″.44	50″.46	−2″.02	49″.45
Small dim light— Mean of 10 single pointings	51″.11	48″.15	+2″.96	49″.63

The figures under the heading "Difference" are double the personal equation of bisection. Thus the personal equation of this observer on the bright light was −1″.01 and on the dim light +1″.48. Had he been measuring the angle between similar dim and bright lights in the field the measurement would have been 2″.49 in error, a very large error for primary triangulation.

Effects of Introduction of Reversing Prism

To remedy the situation the telescope was fitted with a right-angled prism in front of the eyepiece, the hypotenuse of the prism being parallel to the line of sight (1, p. 147). As the field of view is reversed horizontally in one position of the prism and not when it is revolved 90°, personal equation should be eliminated from the mean of two pointings taken with the prism in the two positions.

TABLE III
ANGLES BETWEEN LIGHTS *A* AND *B*

Image reversed or direct (*R* or *D*)	*A* bright and *B* dim	*A* dim and *B* bright
	4° 23′	4° 23′
R	57″.0	56″.3
D	55″.9	57″.6
R	57″.8	56″.2
D	56″.0	57″.2
R	58″.0	56″.3
D	57″.8	57″.5
R	56″.3	56″.6
D	56″.9	57″.5
Mean	56″.96	56″.90
Mean of 4 measures (Image R)	57″.28	56″.35
Mean of 4 measures (Image D)	56″.65	57″.45

To show the effect of this attachment two sets of horizontal angles were measured by this observer between two lights, *A* and *B*; in the first set the left light, *A*, was fairly bright while the right, *B*, was dim; in the second set the left, *A*, was dim and the right, *B*, bright. First, two measurements were made on the first set, then four on the second set, then four on the first set, etc., ending with two readings on the first set to compensate for any gradual change in the positions of the lights. Alternate measurements were made with "image reversed horizontally" and "image direct horizontally". Each measurement

was the mean of two rounds, one clockwise with telescope "direct" followed by an anticlockwise round with telescope "reversed". Table III exemplifies the results obtained.

The effect of varying personal equation of bisection is evident in the set in Table III; also, any error due to it is eliminated by reversing the image, since the means of the two sets (56″.96 and 56″.90) are almost identical.

Lights of such different intensity as were used in some of the above tests are seldom met in actual practice, so that errors of the large amounts indicated in some of the tests are not probable. In addition it is most likely that few observers exhibit such large changes in their personal equation of pointing as are indicated above. At the same time much greater variations in the appearance of lights occur in field practice than it is reasonable to try to reproduce in a laboratory test and, as the personal equation varies with the aspect of the lights or objects sighted on, it is impossible to predict what magnitude of errors may or may not be introduced into the field work as a result of varying personal equation.

Varying Personal Equation when Sighting on Collimators

One might anticipate that angles measured between collimators containing cross wires at their foci would not be seriously in error owing to changing personal equation. Table IV shows that even the small differences between the appearance of the marks in individual collimators may produce changes which are important.

TABLE IV

DIFFERENCE BETWEEN ANGLE MEASUREMENTS BY TWO OBSERVERS ON FOUR COLLIMATORS *A*, *B*, *C* AND *D*

Angle	No. of measurements by each observer	Average difference between observers	No. of plus differences	No. of minus differences
A to *B*	14	+0″.61	13	1
B to *C*	12	+0″.04	6	6
C to *D*	12	−1″.49	1	11
D to *A*	18	+0″.60	15	3

Each of the measurements noted in Column 2, Table IV, was the mean of four rounds, two clockwise with telescope "direct" and two counter clockwise with telescope "reverse". Each of the angles was therefore measured with more than "primary triangulation" precision. It is believed that the probable accidental error of the total measurement of each angle between collimators by each observer separately was less than ±0″.1 of arc. In this case the difference between the measurements by the two observers of the angles *A* to *B* and *D* to *A* was at least six times the probable error of each observer's total measurement while the difference of the angle *C* to *D* was at least 15 times the probable error.

Varying Personal Equation under Field Conditions

To determine what differences, if any, might be expected under field conditions a set of readings was taken by the previously mentioned observer on four field lights from triangulation station Ottawa. The character of the four lights was intentionally made different; those on Duntile and Museum were apparently normal field lights; that on Jackson was made small and faint, a frequent field condition; that on Billings was made as large and bright as is ever encountered under field conditions. Table V gives the angles to the various stations from the initial, Duntile.

TABLE V

ANGLES BETWEEN FIELD LIGHTS

Station	Duntile	Jackson		Museum		Billings	
Light	Light normal	Light small and faint		Light normal		Light large and bright	
Image		Direct	Reversed	Direct	Reversed	Direct	Reversed
	0° 00′ 0″	153° 07′		174° 56′		233° 15′	
		17″.1	16″.3	50″.0	49″.7	50″.8	48″.3
		15″.8	17″.0	50″.3	49″.4	51″.4	49″.5
		16″.0	17″.3	50″.0	49″.0	50″.1	46″.5
		14″.6	16″.7	49″.2	48″.8	49″.5	49″.7
		15″.8	17″.4	49″.2*	49″.4*	49″.0	49″.1
		16″.2	16″.4	49″.3*	48″.7*	51″.2	48″.4
		14″.8	15″.6	48″.1*	49.″7*	50″.7	47″.9
		14″.8	16″.1	48″.5*	47″.5*	51″.2	46″.4
Mean	0″	15″.64	16″.60	49″.32	49″.02	50″.49	48″.22
Grand mean		16″.12		49″.17		49″.35	

**In the last half of the set the appearance of Museum light changed owing to drifting smoke.*

The effect of varying personal equation of bisection is evident in the set in Table V. From what has been said previously it is not surprising that the sign of the personal equation changes on Jackson (faint) and Billings (bright). It is, perhaps, of greater significance that there is strong evidence of varying personal equation even in the measurement of the angle between the two apparently normal lights Duntile and Museum.

It is to be borne in mind that the above readings were taken by the engineer who was previously mentioned as being a very consistent observer but who had shown evidence of having a large varying personal equation. Other observers have not shown such large variations in laboratory tests.

In a subsequent extended field test, strong evidence existed that angular errors, by various observers, as large as half a second of arc were eliminated by the use of a reversing prism on the telescope.

Reference

1. GLEICHEN, A. Theory of modern optical instruments. His Majesty's Stationery Office, 1918.

IMPROVING THE PERFORMANCE OF PRIMARY TRIANGULATION THEODOLITES AS A RESULT OF LABORATORY TESTS[1]

By J. L. Rannie[2] and W. M. Dennis[3]

Abstract

The lighter types of geodetic theodolites developed during the past decade have permitted considerable economy to be effected in field operations, but have introduced problems of their own. A systematic investigation of one make of these theodolites has been concluded by the Geodetic Survey of Canada in co-operation with the National Research Council and has resulted, first, in the development of a form of test to ascertain the existence of certain errors and, second, in the correction of these errors by improvements to the axis system of the theodolites.

Preliminary

The Wild Precision Theodolite

This lightweight type of primary triangulation theodolite has been used since 1928 by the Geodetic Survey of Canada, Department of the Interior. One of these instruments is illustrated elsewhere (2, Fig. 3). It is noteworthy for the ingenuity and compactness of its design; the circles are of glass and are read through a microscope parallel and close to the telescope. By the adoption of these theodolites considerable economy has been possible in field work owing to the convenience and speed of operation and to the relative ease of transport, particularly in rough country.

Field Experiences

Naturally an innovation is the subject of suspicion until it justifies itself, and a careful check was kept of the field performance of the Wild instruments. There are difficulties in this course owing to the presence of so many sources of error external to the instrument, mainly atmospheric ones. In all cases, however, the individual readings of the Wild theodolites agreed as well among themselves as did those of the older instruments, indicating that accidental errors such as telescope pointing, micrometer reading and circle graduation errors were certainly not excessive. Furthermore, during at least one field season the triangle misclosures, side equation tests, length and azimuth misclosures were all well within the tolerances allowed. While in other cases an unusually large number of stations had to be re-occupied to obtain the required precision, it could not be said definitely that the Wild theodolite was the seat of the trouble.

Before the investigation described below was begun there were only two disquieting features noticed in the Wild theodolites, though in neither case was their exact relation to angular errors fully appreciated. One was that the alidade axis of several theodolites had developed tightness during service and these axes had had to be lapped to remove this. The other feature was "creep" about which more is said later. This was found to a greater or less

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degree in several of the 10 Wild theodolites in the possession of the Geodetic Survey, and naturally gave rise to the feeling that all was not as it should be. Consequently means were sought to ascertain whether there were any sources of error inherent in this particular form of theodolite.

Outdoor Test

Tests of telescopes, circles and other features were made from time to time, but yielded no indication of anything being wrong. Consequently an endeavor was made to develop a test that would indicate the minute differences of the order anticipated between different instruments.

First, a field test was made in which theodolites of different types were used to measure angles from a single station. In this test Wild theodolite No. 558* was compared with two 12-in. instruments of conventional design which had given satisfactory field service over a period of years. The results indicated that No. 558 had a lower grade of performance than the older instruments.

Laboratory Test

Winter having set in attention was given to laboratory tests. In these it is possible to obtain better control of the conditions and generally more easily isolate the effect of any one source of error. Through the co-operation of the Division of Physics and Engineering of the National Research Council, the tests were accordingly transferred to the Physics Laboratory of the Council, using the collimator system established there for surveying instrument standardization.

The apparatus is housed in a sub-basement room where the temperature rarely changes by as much as 1° F. during a day. Fig. 1 is a diagram showing the location of the collimators. These are supported on concrete piers and an adjustable heavy cast iron stand supports the theodolite. During the tests the collimators were covered by cloths, and reasonable precautions were taken to avoid errors due to the heat of the observers' bodies and other disturbing elements. The collimators were found to retain their angular spacing in a very satisfactory manner, but as a further safeguard the test program was so arranged that the effect of any regular movement of a collimator would be compensated in computing the final results.

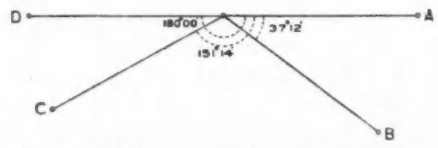

FIG. 1. *Spacing of collimators used in laboratory tests.*

Test Program

In developing a test program it is necessary to evaluate not only accidental errors but systematic errors, and the latter may be much the more important

* *Individual instruments are given their Geodetic Survey numbers.*

and difficult to discover. The former may be evaluated by a comparison of probable errors derived from independent tests of various types of theodolites, and if tests of several instruments which have given satisfactory field performances over a period of years be used as a standard, the capabilities of any other types can be determined by comparison with the standard, as far as accidental errors are concerned.

There is danger, however, that this class of test will sometimes fail to reveal systematic errors, since these errors are liable to repeat themselves and will not be indicated as large residuals. Systematic errors are more likely to be disclosed by a comparison of probable errors derived from an actual comparison of the measurements of the same angles by different types of theodolites, since it is improbable that these errors will be duplicated in the different types. By treating all errors as accidental in calculating probable errors of measurement, the existence of systematic errors is likely to be revealed by a large increase in the probable errors so calculated over those relating to accidental errors.

The ideal program of test should be capable of having the results of each instrument reduced independently and also in combination with others.

With the collimator equipment employed it was found that minute errors in focusing collimators and theodolites, together with very small differences of centering of different theodolites, produced unexpectedly large differences in the measured values of the angles, so that the laboratory test had to be confined to a comparison of independent tests of different theodolites as noted above. In this test systematic errors could be revealed only by varying the conditions which produced them in different sections of the test so that these errors appeared in the form of large residuals which, when used in formulas for accidental errors, produced large probable errors. This necessitated a prior knowledge of the existence of these systematic errors so that the form of the test could be designed to reveal them.

The full test program for a theodolite comprised four independent parts, so arranged that each part could be completed in from three to four hours. The method of angle measurement was as follows:—

A round of telescope pointings and circle readings with telescope "direct" was made on successive collimators in a clockwise direction, closing on the selected initial, followed by a corresponding round in a counterclockwise

TABLE I

HORIZONTAL CIRCLE AND MICROMETER DRUM READINGS WHEN THE TELESCOPE IS DIRECTED ON THE INITIAL COLLIMATOR FOR DIFFERENT "POSITIONS"

Position no.	Circle	Drum	Position no.	Circle	Drum	Position no.	Circle	Drum
I	0° 00′	10	VII	112° 00′	35	XIII	34° 00′	10
II	45° 00′	25	VIII	157° 00′	50	XIV	79° 00′	25
III	90° 00′	35	IX	11° 00′	10	XV	124° 00′	35
IV	135° 00′	50	X	56° 00′	25	XVI	169° 00′	50
V	22° 00′	10	XI	101° 00′	35			
VI	67° 00′	25	XII	146° 00′	50			

NOTE:—*These are the settings used for the Wild theodolite. Theodolites with other dispositions of micrometers, graduations and drum readings have appropriate settings.*

direction with telescope "reverse", *i.e.*, after transiting the telescope. This is called a "position". In the program outlined in Table I "positions I, II, III–XVI" refer to the setting of the circle when the telescope was pointed on the collimator chosen as the initial, as given in Table I.

Part I of the full test program is shown in Table II.

TABLE II

PART I OF THE FULL TEST PROGRAM

Collimators pointed on in the order	Position	Observers
A B C D A	I–IV	*A* and *B*
B C D B	I–IV	*A* and *B*
C D C	I–IV	*A* and *B*
C D C	V–VIII	*A* and *B*
B C D B	V–VIII	*A* and *B*
A B C D A	V–VIII	*A* and *B*

The other three parts have only slight variations from the above. Part 2 starts on collimator *C* instead of *A*, and the circle is read on positions IX to XVI instead of I to VIII; Part 3 begins on collimator *B*, and the circle is read on positions I to VIII; Part 4 begins on collimator *D*, and the circle is read on positions IX to XVI.

An example is given in Table III of the reduced readings obtained in one part of the test program (Part 1; Theodolite No. 1).

TABLE III

REDUCED READINGS OBTAINED IN ONE PART OF THE TEST PROGRAM

Observer	Position	*A*	*B*	*C*	*D*	Closure
		0° 00′	37° 11′	151° 13′	179° 59′	359° 59′
E.M.M.	I	00″.0	56″.5	42″.6	35″.0	59″.5
E.M.M.	II		56″.9	43″.0	34″.9	59″.5
G.F.D.	III		54″.9	40″.8	34″.1	59″.9
G.F.D.	IV		54″.7	41″.3	33″.0	59″.6
E.M.M.	V		54″.4	41″.3	33″.9	60″.1
E.M.M.	VI		57″.5	42″.5	34″.7	60″.2
G.F.D.	VII		58″.0	41″.5	34″.5	60″.9
G.F.D.	VIII		55″.2	39″.4	34″.2	60″.3
Mean		00″.00	56″.01	41″.55	34″.29	60″.00
Mean, corrected for closure			56″.01	41″.55	34″.29	
			0° 00′	114° 01′	142° 47′	359° 59′
E.M.M.	I		00″.0	46″.6	40″.1	60″.6
E.M.M.	II			46″.3	38″.9	59″.5
G.F.D.	III			44″.7	37″.2	59″.5
G.F.D.	IV			43″.9	37″.1	59″.5
E.M.M.	V			46″.0	38″.4	59″.9
E.M.M.	VI			45″.9	38″.2	59″.4
G.F.D.	VII			44″.5	39″.6	60″.6
G.F.D.	VIII			45″.6	38″.2	61″.0
Mean			00″.00	45″.44	38″.46	60″.00
Mean, corrected for closure				45″.44	38″.46	
				0° 00′	28° 45′	359° 59′
E.M.M.	I			00″.0	53″.0	59″.9
E.M.M.	II				53″.2	59″.7
G.F.D.	III				51″.8	59″.4
G.F.D.	IV				52″.9	60″.5
E.M.M.	V				51″.6	60″.2
E.M.M.	VI				53″.5	60″.7
G.F.D.	VII				53″.3	60″.5
G.F.D.	VIII				52″.4	61″.0
Mean				00″.00	52″.71	60″.24
Mean, corrected for closure					52″.59	

NOTE:—*The readings of this set were not taken in the above order, but have been rearranged for ease of computation. The order of taking the readings is indicated in Table II.*

The method of adjustment of the sets is outlined elsewhere (2). As an example the result of the adjustment of the set in Table III is given in Table IV,

TABLE IV

RESULT OF THE ADJUSTMENT OF THE SET IN TABLE III

Angle	Adjusted	Measured	v	Angle	Adjusted	Measured	v
A–B	55″.99	56″.01	−0″.02	*B–C*	45″.57	45″.44	+0″.13
A–C	41″.56	41″.55	+0″.01	*B–D*	38″.31	38″.46	−0″.15
A–D	34″.30	34″.29	+0″.01	*C–D*	52″.74	52″.59	+0″.15
							$\Sigma v^2$0″.0625

from which is obtained

$$r_8 = \pm 0.6745\sqrt{\frac{\Sigma v^2}{n-q}} = \pm 0.6745\sqrt{\frac{0.0625}{6-3}}$$

$$r_{16} = \frac{r_8}{\sqrt{2}} = \pm 0''.069$$

which gives the probable error of the measurement of an angle in 8 and 16 circle positions. The latter is the form used throughout this paper.

As indicated on page 349 the full test on each theodolite was divided into four parts, each similar to the above, and the mean of the four probable errors is considered the value for that full test.

Standard Probable Error

The results of the full test program described previously with three theodolites of older patterns which had given satisfactory results over a period of years, and with one Wild theodolite, are given in Table V.

TABLE V

MEAN PROBABLE ERRORS OBTAINED WITH THREE THEODOLITES OF OLDER PATTERNS AND ONE WILD THEODOLITE

Part	Two-micrometer theodolite No. 1	Three-micrometer theodolite No. 2	Two-micrometer theodolite No. 3	Wild theodolite No. 558
1	±0″.069	±0″.114	±0″.112	±0″.113
2	±0″.106	±0″.090	±0″.046	±0″.101
3	±0″.035	±0″.142	—	±0″.105
		±0″.058		
4	±0″.120	±0″.092	—	±0″.105
Mean	±0″.083	±0″.099	±0″.079	±0″.106

As a result of this and other similar tests a probable error of ±0″.1 was decided on as a standard of accidental errors by which the performance of various theodolites could be judged, when subjected to the full test program on collimators as outlined above.

The usefulness of the probable error $\pm 0''.1$ as a standard of comparison depends on the employment of the same laboratory equipment and observational program throughout the tests and on calculating the probable errors on the same basis in all cases. Probable errors have, in this investigation, been based on a comparison of the *averages* of eight measurements of various angles, and no account has been taken of the divergence of individual measurements. Anyone making similar tests would have to develop his own standard based on his instrumental equipment, observational program and basis of computing probable errors.

It is to be stressed in regard to the above program that the probable error is simply a measure of the *agreement* of average measurements of angles. It is not necessarily a measure of the *accuracy* of the angle measurement. If, for example, the readings on a certain collimator contained any systematic error throughout the program the probable error would be no larger than if the systematic error did not exist, but the angles as measured would be in error by that constant amount. Only by changing the conditions in different sections of the test, so that any systematic error appears at different places in the various sections, is that systematic error revealed by means of a larger probable error.

This is the reason why Wild theodolite No. 558 shows up well in comparison with others in Table V whereas, as mentioned on page 348, the outdoor test showed it to be inferior. In later variations of the tests systematic errors were indicated in this theodolite (see Table IX).

Possible Sources of Error

When a few test results were obtained it was decided to take stock of the situation. The facts given below were not all arrived at in the order shown, but can be appreciated better when set out in sequence.

First of all the following definite information had been acquired:—

(i) Creep existed to a greater or less degree in six of the 10 Wild theodolites. Creep was the name given to the following characteristic. If telescope pointings are made after the theodolite has stood for some time with the telescope directed approximately on an object, the pointing will not change. If, however, the telescope is pointed and the circle read immediately after the alidade has been rotated through 360°, pointings and circle readings may creep for a period perhaps as long as eight minutes and by various amounts up to six or seven seconds of arc.

Creep varied greatly in different theodolites. In some it was consistent and unmistakable, sometimes it occurred only at certain circle readings, in one or two it was found only after the telescope had been transited, while in other cases it was present but difficult to detect. One theodolite, previously free from creep, developed it after the alidade axis had been lapped to improve the ease of rotation. It was evidently caused by a lateral movement of the alidade within the limits of the upper locating bearing of the alidade axis, owing to some imperfection of the axis system—alidade or telescope, or both.

(ii) Conflicting results were obtained in the outdoor and laboratory tests with Wild theodolite No. 558. The former indicated a definitely lower precision for No. 558 in comparison with older types, whereas the latter test (see Table V) had shown very little, if any, inferiority for this theodolite. The latter test apparently failed to reveal whatever faults existed.

(iii) The alidade axis of some of the Wild theodolites had developed tightness during service, and these axes had had to be lapped to eliminate this. This fact definitely indicated warp of the metal.

The Wild theodolite is constructed with cylindrical steel telescope and alidade axes, and these parts are fitted with very small tolerances, the fits and workmanship approximating to the type of work usual in gauges and machinists' tools.

The following suggestions were therefore brought forward:—

(a) No matter how nearly perfect the workmanship there is always an error due to the actual forms of cylinders and surfaces not exactly conforming to the ideal geometrical shapes they are designed to have.

(b) Many metals, particularly in the first few years after they have been heated or deformed in mechanical operations are subject to dimensional changes. This fact is well known in workshops, where, despite elaborate precautions, it often leads to trouble. Steel gauges show secular variations (4), and even the bronze Imperial standards of length have shown progressive changes (3).

(c) As a corollary to (a) and (b), if the tolerances between parts that move relatively to one another are small it is quite possible to see how defects may develop in an instrument which is free from them at the time of construction. This is particularly the case with cylindrical fits having very small tolerances.

Strain

As both the horizontal and the vertical axes of the Wild theodolite fall within this category it began to be realized how errors of angle measurement might occur. The following example shows what can take place in the transfer of strain:—

In one Wild theodolite the prism holder in the side of one standard which, when turned to and fro, permits the horizontal and vertical circles to be read, was found to be improperly fitted in its box and there was a slight jamming of the prism holder as it was turned. With the prism set to view one circle the telescope axis worked freely, but with the prism set to view the other circle the telescope was very stiff on its axis—a clear case of strain in the prism box twisting the standard and communicating the strain to the cylindrical telescope axis. One can easily visualize a horizontal deflection of the telescope in such a case.

One dangerous feature of axis strain is that, unless it is excessive, it can be detected and localized only by a specially designed test, with apparatus which is not always available to a surveying organization. It may not be

noticeable by any "feel" of definite stiffness; also while appreciable stiffness may be due to strain it may be due to gummy oil on the axes. Axes known to be free from strain, but which have not been cleaned and re-oiled for several months, may "feel" stiffer than axes known to contain strain but which have just been cleaned and oiled.

Another dangerous feature of changing axis strain is that it is not detected by the ordinary standards of comparison used in field practice, such as the agreement of the various measurements of angles, and is not eliminated by the repetition of observations.

Another consideration was that if there were some strain in the telescope axis, elevation or depression of the telescope between sights on different stations could vary the amount of strain and so result in a relative movement between the collimation axis and the reference line of the horizontal circle micrometer. Further possible errors might arise from warping of the male and female alidade axis with consequent variable strains at different azimuths of the telescope.

It should be emphasized, too, that there are several possible sources of strain which may finally result in errors of horizontal angle measurement. The axis systems (alidade and telescope) together with their connections to the standards, must be considered as a unit; any strain in any part of the unit may react on any other part; for satisfactory performance the possibility of strain being introduced to any part of it must be eliminated entirely.

Detecting Axis Strain in Wild Theodolites

The first definite indication that a theodolite was not giving accurate results came from an analysis of rounds of readings, either on field lights or on collimators. It was noticed that the difference between direct and reverse readings—on horizontal sights this equals double the collimation error—was not always the same on all of the objects sighted on; in other words some of the angles measured with "telescope direct" were consistently different from those with "telescope reverse". One notable example occurred during a field test in 1932 in the measurement of an angle of about 185° with Wild theodolite No. 561, in which noticeable stiffness due to warping of the alidade axis existed.

Each of the sixteen measurements indicated the same trend as the means shown in Table VI.

TABLE VI

DIFFERENCE BETWEEN DIRECT AND REVERSE READINGS

—	Difference between direct and reverse readings		Angle between Station *A* and Station *B*	
	On station *A*	On station *B*	Telescope direct	Telescope reversed
			185° 03′	
Mean of 16 measurements	04″.84	01″.29	03″.96	07″.51

The angle shown in Table VI was the only angle in a round of four which showed trouble of this order of magnitude. This indicated that, while a systematic error of some kind existed in this instrument, it varied at different azimuths of the telescope. Variable strain in the alidade axis was suggested as the cause of this systematic error.

TABLE VII

DIFFERENCE BETWEEN DIRECT AND REVERSE READINGS (MEANS OF EIGHT RESULTS IN EACH CASE)

B	*C*	*D*	*A*	Closure
11″.72	10″.11 10″.82	10″.27 09″.79 11″.00	12″.38 11″.75 12″.00	11″.78 10″.92 10″.96

Another example of the same occurrence, though much smaller in amount, when sighting on collimators, is given in Table VII.

It is apparent that the results on collimator *A* are uniformly larger than on other collimators, while those on *C* and *D* are smaller.

It was realized that errors in angle measurement produced by axis strain could be detected in the laboratory only by changing the positions of the leveling screws, thus altering the relation of the alidade axis and its socket. Test angles were therefore measured between two collimators, the leveling screws being placed in three positions 120° apart in each third of the test.

TABLE VIII

ANGLES MEASURED WITH THEODOLITE WITH STRAINED AXES

Marked footscrew at	Angle (seconds only) between collimators *A* and *B*
0°	38″.54
120°	37″.80
240°	40″.24

Table VIII shows the difference fairly plainly; the results in each case are the means of 16 rounds of readings, eight with telescope direct and eight with telescope reverse, in eight positions of the horizontal circle.

The three mean values should have a maximum variation of two- or three-tenths of a second (see Table XI), and it is evident that a different systematic error existed in each third of the measurements; the cause could be due only to changing strain in the alidade axis, as no other factor was altered.

A method had now been found for detecting the effect of strain, and this method could be conveniently applied to each part of the full test program outlined in Table II. Each third of each part of the program was taken with the footscrews in different positions, and the probable error of an angle was calculated in the same manner as before, treating systematic errors as accidental ones. Table IX illustrates the probable errors derived from this type of test.

For comparison, the results with Wild No. 558 without interchanging

TABLE IX

PROBABLE ERRORS WITH THEODOLITES WITH STRAINED AXES

Part	Wild No. 558	Wild No. 562
1	±0″.151	±0″.219
2	±0″.102	±0″.065
3	±0″.262	±0″.139
4	±0″.240	—
Mean	±0″.189	±0″.141

the position of the footscrews, as shown in Table V, may be consulted. These mean probable errors are obviously larger than the standard of comparison ($\pm 0''.1$), and these theodolites, among others, were judged to have strained axes.

All of the evidence, of which the above are only examples, indicated that angular errors of appreciable magnitude—of the order of 2″ to 4″—may have resulted from strain or other axis trouble in at least nine of the 10 Wild theodolites examined. Attention was then devoted to its elimination.

New Axis Design

As stated previously, geometrical precision is not possible in practice, and even when closely approached its permanence is questionable. Attention was hence devoted to securing a form of axis system in which the unavoidable inexactitude in manufacture or secular change would have no effect on the instrument indications. A well known method is to apply the principle of kinematical design (1). In the new form every endeavor was made to introduce as few changes as possible to the theodolites. For a new instrument it would be possible to improve and extend the changes here described. The changes indicated below were made in the shops of the National Research Council. About four days were required by one instrument maker to complete the mechanical work on each theodolite.

Alidade Axis

Figs. 2*a* and 2*b* show the original and modified alidade axes respectively.

A three-point ball bearing (1 in Fig. 2*b*)—three balls only were used in the first cases, but as it was feared that damage might occur from vibration during transit, nine balls were fitted later—replaces the ball thrust bearing (2 in Fig. 2*a*) and plain cylindrical locating bearing (3 in Fig. 2*a*). At the lower end of the axis (4 in Fig. 2*b*) two-thirds of the length of the bearing was relieved, so that there would be negligible constraint with a slightly warped axis. This end of the bearing is not subject to much load and needs to have only sufficient surface to resist ordinary wear. A better design might be two solid pads placed 120° apart with a third spring supported pad. This design could not be employed in this instrument without large changes of design.

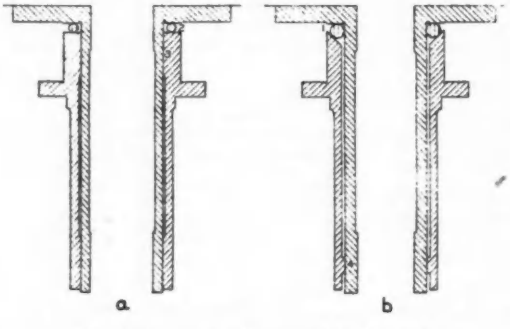

FIG. 2. *Original and modified alidade axis.*

There was strong evidence that the lower part of the original axis was too tight in some cases as, even with the remodeled axis, the tolerance of the lower bearing surface had

to be increased before improved results were obtained. It was found to be safer to have the lower bearing slightly loose than the least bit tight.

Telescope Axis

As indicated in Fig. 3, at each end of the telescope axis two-thirds of the length of the bearing cylinder was relieved to reduce the likelihood of strain being communicated through these bearings to the collimation axis, and a circumferential section of 60° was relieved entirely at the top of the bearing. By this latter device there was avoided the fault called "roll and slip" which had been found in several of the theodolites. This is the slight tendency of the telescope axis to climb in its bearing as the telescope is revolved. In the exaggerated case shown in Fig. 4, where the outer cylinder revolves on the inner one, the first action is a rolling motion, and the point of contact moves from M to M'. As the motion continues the position of M' changes and may return to M. It is quite easy to realize that, owing to the lack of exact symmetry already mentioned, the roll and slip may not be the same at both ends of the telescope axis and slight deflections of the telescope result. This fault was definitely detected during some of the tests and showed itself by irregularities in readings shortly after the telescope was transited.

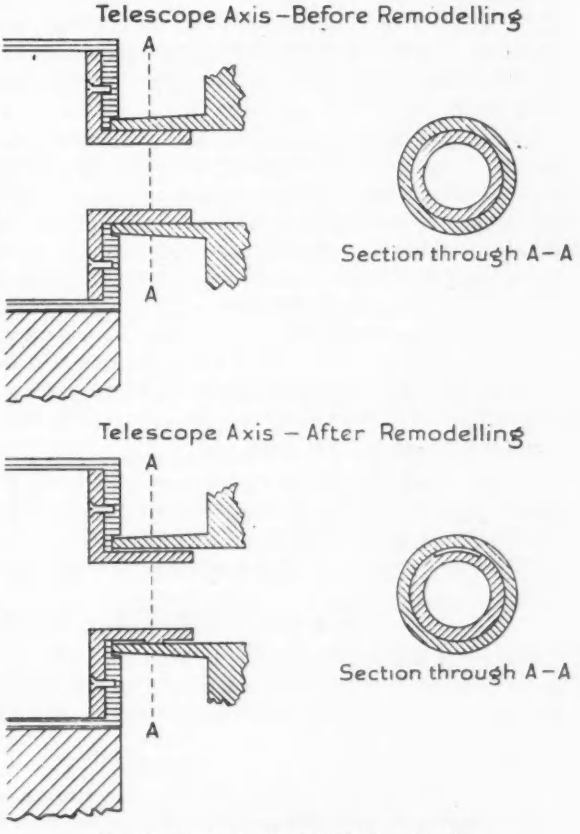

FIG. 3. *Original and modified telescope axis.*

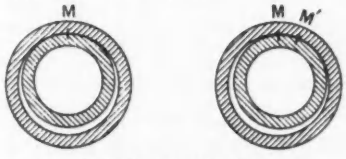

FIG. 4. *Roll and slip of telescope axis.*

One other small source of trouble was traced to the telescope axis. The small horizontal spring which actuates a horizontal plunger through which the electric current is transferred from standards to telescope was found to be too strong and this accentuated the climb of the axis.

It is needless to add that workmanship of the highest grade is necessary in fitting the new axes, but it is felt that, while no amount of skill can preclude the possibility of strain errors with the older type, with reasonable care in the shop, troubles of this nature should not occur with the new form. It may be added that the new type of axis should be cheaper to construct than the older form.

In assembling the remodeled telescope axis the following procedure is largely independent of "feel". The block containing the micrometer at the top of one standard has two fixed dowels; this block is screwed tight. Any adjustment is made with the block on top of the other standard, the screw dowel of which is removed. The free block is then moved sideways until the telescope tightens in the fixed block; it is then moved to the other side until the telescope again tightens on the other side of the fixed block. The mean of these two positions of the free block is used as the proper position. Straight edges are then placed along the outer edges of the two blocks and the free block is twisted until the straight edges are parallel. A small amount of end play in the telescope is advisable. The block is then screwed tight, the screw dowel being left out.

If it is found that the two ends of telescope axis are not truly in line or if the cylindrical bearing surfaces are not square with the outer faces of the blocks preliminary adjustments are required.

No further trouble has been experienced with this modified telescope axis.

Tests with Modified Wild Theodolites

Following the remodeling each instrument was subjected to the full test program described above employing the same observers. Table X exemplifies the probable errors derived from the remodeled theodolites.

TABLE X

PROBABLE ERRORS DERIVED FROM THE REMODELED THEODOLITES

Part	Wild No. 554	Wild No. 558	Wild No. 559	Wild No. 560	Wild No. 561
1	±0″.080	±0″.089	±0″.117	±0″.100	±0″.073
2	±0″.038	±0″.068	±0″.042	±0″.041	±0″.060
3	±0″.084	±0″.099	±0″.085	±0″.105	±0″.032
4	±0″.109	±0″.070	±0″.055	±0″.076	±0″.105
Mean	±0″.079	±0″.081	±0″.075	±0″.080	±0″.068

These mean probable errors are smaller than the standard set for comparison purposes (±0″.1) and are still smaller than those obtained with

similar theodolites which exhibited strained axes. It has therefore been concluded that systematic errors have been eliminated from these theodolites and that accidental errors have been slightly reduced.

It is interesting to note how the theodolite with remodeled axes acts compared to its action with strained axes. An angle was measured between two collimators with the footscrews moved between sets with the following results. Each of the results in Table XI is the mean of 16 rounds of readings, eight with telescope direct and eight reverse, in eight positions of the horizontal circle.

TABLE XI

ANGLES MEASURED WITH THEODOLITE WITH REMODELED AXES

Marked footscrew at	Angle (seconds only) between collimators *A* and *B*
0°	51″.68
120°	51″.65
240°	51″.64

Again, consider the differences between direct and reverse readings on different collimators with a theodolite with remodeled axes (Table XII).

TABLE XII

DIFFERENCE BETWEEN DIRECT AND REVERSE READINGS (MEANS OF EIGHT RESULTS IN EACH CASE)

D	*A*	*B*	*C*	Closure
14″.38	14″.08	14″.21	14″.13	14″.36
	14″.25	14″.05	14″.24	14″.13
		14″.13	14″.18	14″.19

The results in Tables XI and XII are strikingly better than those shown in Tables IX and VIII and indicate that axis trouble has been largely eliminated.

Observational Procedure to Reduce Effect of Strain and Roll

There will be operators of Wild theodolites who cannot conveniently test their instruments to determine whether they have strained axes, or who cannot conveniently have the changes made which are suggested in this paper, but who wish to obtain the best results of which their instrument is capable. The following precautions and observation procedure are suggested by this investigation.

1. The footscrews must be adjusted tighter than is necessary with heavier theodolites. Even with the footscrews tight, however, there may be unsteadiness of the theodolite owing to the casing of the footscrew assembly (*a*, Fig. 5), which screws into the base of the theodolite, being imperfectly seated at the contact shown by the arrows in Fig. 5. Where this is the case a marked improvement in the steadiness of the theodolite is obtained by unscrewing the assembly from the base, after removing the grub screw, and scraping the base to give a perfect seating.

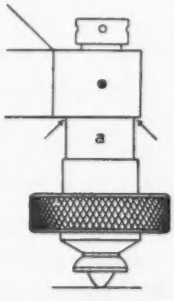

FIG. 5. *Imperfectly seated casing of footscrew assembly is a possible cause of instability of theodolite.*

2. If there is any suggestion of stiffness in the action of the alidade axis it should be lapped to a loose fit. "Wobble" of the axis, contrary to most beliefs, is not a serious fault, and a slack centre is preferable to a tight one.

3. The most meticulous care should be taken to avoid any stiffness in the telescope action at any point. First the blocks at the tops of the standards should be manip-

ulated to obtain the utmost freedom of action. If stiffness cannot be eliminated in this manner it may be necessary to dismantle the vertical circle case (six screws hold the two halves together) and other parts of the axis, carefully work the plane surfaces and exercise great care in replacing the screws to obtain even tension.

4. The tests have demonstrated that axis strain acts differently as the telescope is swung in azimuth. To minimize its effect the leveling screws should be changed in position as frequently as possible. For instance, any program might be divided into three parts and the leveling screws moved 120° between parts.

5. Whenever the telescope is moved the top centre of the telescope might be tapped to avoid error due to roll and slip.

Appendix

Other Probable Errors

In the test program described above the circle is closed in the middle of each position, *i.e.*, the telescope is pointed on the initial in the middle of each position before and after reversing the telescope. The error of closure provides the data for calculating the probable error of a measurement of an angle due to combined telescope pointing and micrometer reading errors.

Similarly for all other directions the differences between the individual position results and the mean of a set give the data for calculating the probable error of an angle due to errors of combined telescope pointing, micrometer reading and graduation.

The effect of graduation errors can easily be separated from that of telescope pointing and micrometer reading.

Telescope, Micrometer and Graduation Errors

The probable errors of measurement due to the above errors were calculated from a full test program with one Wild theodolite and with two older-type theodolites which had given years of satisfactory service.

TABLE XIII

PROBABLE ERRORS OF ANGLE MEASUREMENT DUE TO POINTING, READING AND GRADUATION ERRORS

Probable error of measurement of angle (r_{15}) due to telescope pointing and micrometer reading errors		Probable error of measurement of angle (r_{16}) due to graduation errors	
Three-micrometer Cooke theodolite	±0″.07	Three-micrometer Cooke theodolite	±0″.13
Two-micrometer Parkhurst theodolite	±0″.09	Two-micrometer Parkhurst theodolite	±0″.16
Wild theodolite No. 558	±0″.08	Wild theodolite No. 558	±0″.13

The data in Table XIII corroborate the conclusions arrived at from other tests, that no trouble from these sources need be anticipated in this

particular theodolite of the Wild type. Similar data exist for a number of other Wild theodolites.

Acknowledgments

The main share of the observations on which this investigation depended were carried on by two officers of the Geodetic Survey of Canada—G. F. Dalton and E. M. Medlen. Invaluable advice and consultation were received from R. H. Field of the Department of Physics and Engineering of the National Research Council. The machine work involved in remodeling the axes of the Wild theodolite was done by A. A. Barks of the National Research Council staff.

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A FIELD TEST OF PRIMARY TRIANGULATION THEODOLITES[1]

By J. L. Rannie[2]

Abstract

A form of test of the accuracy of precision theodolites is described in which angles were measured out of doors at night with different instruments, the targets being small lights placed at about two miles from the observing station. Probable errors computed from the observations were the basis of comparison and it is shown how these were derived and employed. This test was complementary to a laboratory test on similar instruments.

Introduction

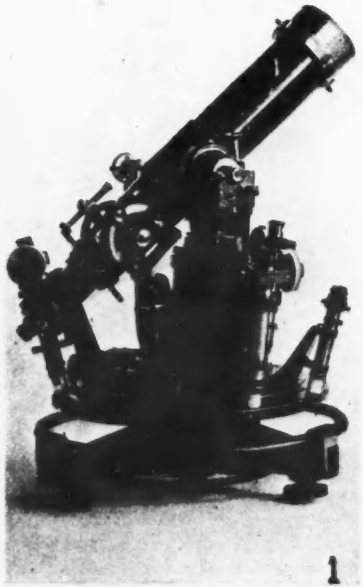
During May, June and July, 1933, an investigation was carried out at Geodetic Survey triangulation station "Ottawa", under conditions approximating those met in field work, to compare the respective capabilities of three triangulation theodolites of different types for correctly measuring horizontal angles. The test was undertaken as a confirmation, under different observational and atmospheric conditions, of conclusions arrived at in the laboratory (3).

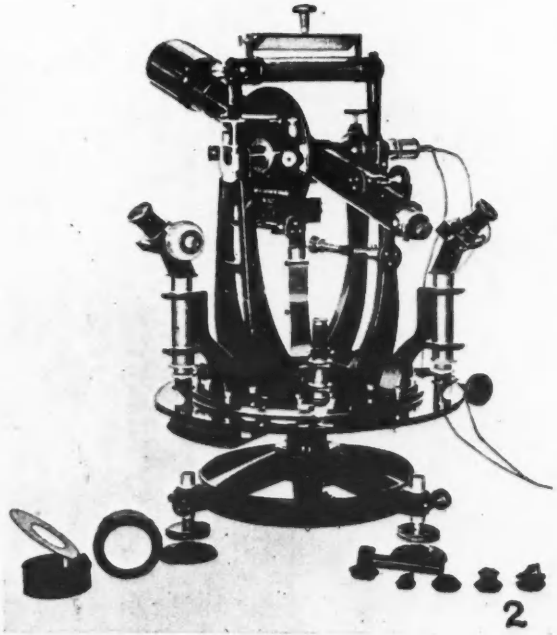
The basis of comparison of different theodolites both in laboratory and field tests was the relative size of the probable error of measurement of an angle, a lower probable error indicating a higher precision.

In the laboratory tests (3) angles were measured on collimators, and unexpected difficulties due to minute errors of focus of the collimators and theodolites and to tiny differences of centering of different theodolites, made it necessary to confine the laboratory investigation to independent tests of each theodolite. While the laboratory test was therefore suitable for the detection of accidental errors and also for such systematic errors as were known to exist, it might not disclose unknown systematic errors. In the field test, errors due to the above causes were negligible so that, in addition to the conclusions based on the performance of independent theodolites, it was possible to base conclusions on a direct comparison of angles measured with two theodolites, and hence disclose any unknown systematic errors. This constituted an important advantage of the field test over the laboratory investigations, and made it valuable as a final confirmation of results reached in the laboratory.

The disadvantages of any field test compared to laboratory tests are several. Delays are occasioned in the field by bad weather; a much larger number of observations is needed in the field than in the laboratory, owing to poorer targets and changing atmospheric conditions, to produce results which may be relied on; owing to the greater uniformity of laboratory conditions any abnormal deviations can be much more easily recognized and traced to their source. For these reasons the bulk of the testing of the theodolites took place in the laboratory, the field test being of a confirmatory nature only.

[1] *Manuscript received January 18, 1934.*
Contribution from the Geodetic Survey of Canada, Department of the Interior, Ottawa.
[2] *Chief of the Triangulation Division, Geodetic Survey of Canada, Department of the Interior, Ottawa.*





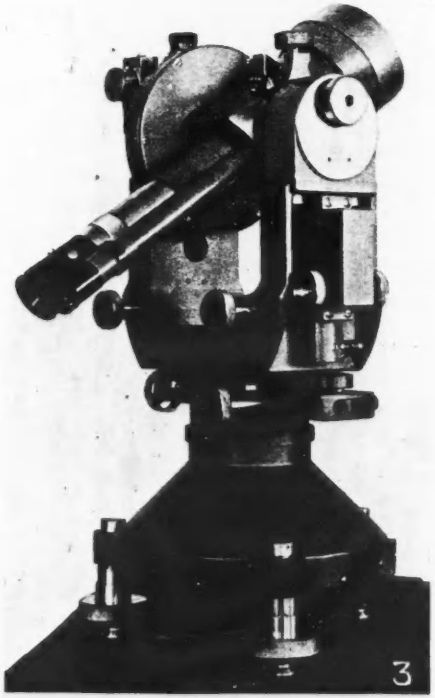


FIG. 1. *Cooke 12-in. three-micrometer theodolite.* FIG. 2. *Kern 12-in. three-micrometer theodolite. For this investigation this instrument was rearranged to make it a two-micrometer instrument.* FIG. 3. *Wild precision theodolite, 5½-in. horizontal circle.*

Theodolites Compared

Theodolites of three types were compared. One theodolite was a heavy Cooke 12-in., three-micrometer microscope instrument; the second was a lighter 12-in., three-micrometer Kern theodolite which was changed before the test by removing one micrometer and re-arranging the other two to make it a two-micrometer theodolite; the third was a Wild precision theodolite with a 5½-in. horizontal circle. The first two theodolites had given satisfactory field performance over a lengthy period. They had more or less conventional steel conical alidade axes with the horizontal or telescope axis lying in open *V*'s; the Wild had cylindrical alidade and telescope axes, and was one which had been shown in the laboratory to be largely free from axis strain and other sources of error. The instruments are illustrated in Figs. 1, 2 and 3.

Layout for Field Test

For the purpose of the test four stations were selected about two miles distant from triangulation station "Ottawa" of the Geodetic Survey of Canada. Fig. 4 shows the disposition of the stations.

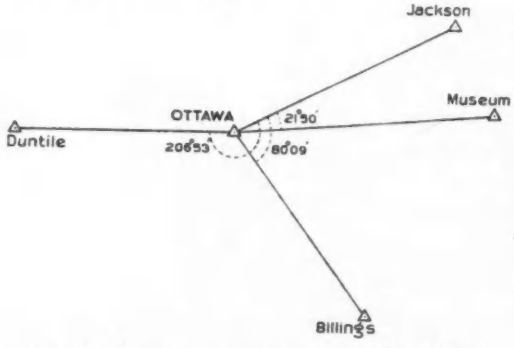


FIG. 4. *Arrangement of stations employed in field test.*

The observing station, Ottawa, was situated about 60 ft. above the ground level on the concrete roof of the stair shaft of the Dominion Observatory. The instrument stand was a wooden tripod cemented to the roof, and the observer stood on a platform separated from the tripod and supported only on the stone walls.

Stations Jackson and Museum were on the roofs of buildings, and the lines to them passed over the city of Ottawa, while Billings and Duntile were ground stations, and the lines to them passed mainly over open country.

All the lines were from 50 to 100 ft. above the buildings or ground along the line for a greater part of the distance.

The targets were small electric automobile headlamps with parabolic reflectors of the type used in Canada on primary triangulation. Current was supplied from the regular city lighting circuit by using small bell-ringing transformers, and the intensity of the lights was regulated by rheostats. The faces of the lamps were covered, except for a centralized vertical slit less than ⅛ in. in width; thus only light from the top and bottom of the reflector was seen from the instrument station. When seen in the telescope under favorable atmospheric conditions the light appeared as two fine dots in a vertical plane, an ideal light for making accurate pointings between the

two vertical wires of the theodolite. Atmospheric disturbances usually tended to fuse and enlarge the dots and made them jumpy, an ordinary field condition, in which case the precision of the telescope pointings was noticeably lowered.

In the telescopes of the Cooke and Kern theodolites the diaphragms were fitted with two vertical spider webs about 30 sec. of arc apart. For pointings, images were placed midway between the two wires. The telescope of the Wild theodolite was fitted with a glass diaphragm having two short, nearly vertical converging lines ruled thereon; at one end the lines were 20 sec. apart and at the other 40 sec.; images of different sizes were placed at such heights in the field of view that there were equal side spaces on different lights between the lines and the image.

Program of Test

The three theodolites were tested in pairs, and the program with each pair was so arranged that the probable error of the measurement of an angle could be calculated in two ways:

1. For each theodolite of the pair, considering only the angular measurements with that instrument.
2. For each theodolite of the pair in terms of the mean result with that pair.

It was anticipated that the first method would give a comparison of the accidental errors of measurement with different theodolites. The second method would in addition indicate whether any systematic errors of measurement existed in any of the theodolites.

The test consisted of nine parts for each pair, each part being independent of the others and being designed to be completed in about three to four hours on one night. The test therefore was completed in 27 nights.

The program comprised the measurement of single and overlapping angles, from an adjustment of which the most probable values of the angles and the above probable errors were derived.

In Table I is given the program of Part 1 for one pair of theodolites.

TABLE I

PROGRAM OF TEST

Theodolite	Position	Circle setting on initial	Points sighted on	Observer
Cooke	I	0°–02′–00″	*J M B D J*	*A*
		0°–02′–00″	*M B D M*	
		0°–02′–00″	*B D B*	
Kern	I	0°–02′–00″	*J M B D J*	*B*
		0°–02′–00″	*M B D M*	
		0°–02′–00″	*B D B*	
Kern	II	90°–03′–00″	*B D B*	*A*
		90°–03′–00″	*M B D M*	
		90°–03′–00″	*J M B D J*	
Cooke	II	30°–03′–00″	*B D B*	*B*
		30°–03′–00″	*M B D M*	
		30°–03′–00″	*J M B D J*	

The other eight parts differed from the above only in the circle readings on the initial and in the station chosen as the first initial. These differences are indicated in Table II.

TABLE II

CIRCLE POSITIONS WITH 3- AND 2-MICROMETER THEODOLITES

Part	Position	Cooke theodolite	Kern and Wild theodolites	First initial	Part	Position	Cooke theodolite	Kern and Wild theodolites	First initial
1	I	0°-02′-00″	0°-02′-00″	Jackson	6	XI	23°-02′-00″	50°-02′-00″	Museum
	II	30°-03′-00″	90°-03′-00″			XII	53°-03′-00″	140°-03′-00″	
2	III	10°-02′-00″	10°-02′-00″	Jackson	7	XIII	6°-02′-00″	60°-02′-00″	Billings
	IV	40°-03′-00″	100°-03′-00″			XIV	36°-03′-00″	150°-03′-00″	
3	V	20°-02′-00″	20°-02′-00″	Jackson	8	XV	16°-02′-00″	70°-02′-00″	Billings
	VI	50°-03′-00″	110°-03′-00″			XVI	46°-03′-00″	160°-03′-00″	
4	VII	3°-02′-00″	30°-02′-00″	Museum	9	XVII	26°-02′-00″	80°-02′-00″	Billings
	VIII	33°-03′-00″	120°-03′-00″			XVIII	56°-03′-00″	170°-03′-00″	
5	IX	13°-02′-00″	40°-02′-00″	Museum					
	X	43°-03′-00″	130°-03′-00″						

In the above program the following points are to be noted:—

1. In the column "Points sighted on" the letters *J*, *M*, *B* and *D* represent stations Jackson, Museum, Billings and Duntile, respectively (Fig. 4).

2. Each set of readings, called a position, consisted of two rounds, one clockwise with telescope "direct" followed by a counterclockwise round with telescope "reverse". The mean of the two constituted a position.

3. The circle settings were distributed equally around the circle.

4. The minutes and seconds of the circle settings were selected to eliminate, as far as possible, any error of "run".

5. The order of making the measurements was designed to eliminate the effect of any regular change in the apparent position of a light due to atmospheric conditions.

6. Frequently a second observer helped in reading micrometers, and took a turn in pointing the telescope. Where this occurred care was taken to have each observer make the pointings as shown in the column headed "Observer".

7. On successive nights the footscrews were changed in position by 120°, so that any differential axis strain might be detected.

8. To eliminate the effect of any variable personal equation of pointing (2) a reversing prism was attached to the eyepieces of the telescopes, and the prism was set to view the image "direct" in the one half of each position and "reversed horizontally" in the other half.

9. To check the action of the theodolite, return readings were made on the initial station in the middle of each set. The mean value of the readings on the initial was used in calculating the angles.

A sample of the reduced readings taken in one part of the above program, rearranged for ease of computation, is shown in Table III.

TABLE III

REDUCED READINGS OF MEASUREMENTS ON ONE NIGHT

Cooke theodolite					Kern theodolite					Sequence of readings	
Jackson	Museum	Billings	Duntile	Closure	Jackson	Museum	Billings	Duntile	Closure	Cooke	Kern
0° 00′	21° 49′	80° 08′	206° 52′	359° 59′	0° 00′	21° 49′	80° 08′	206° 52′	359° 59′		
00″.0	34″.3	33″.8	44″.1	59″.7	00″.0	34″.6	34″.7	44″.7	59″.4	1	4
	33″.8	34″.3	44″.3	59″.7		34″.8	34″.9	43″.2	60″.5	12	9
	*34″.05	34″.05	44″.20	59″.70		34″.70	34″.80	43″.95	59″.95		
	†34″.20	34″.20	44″.35			34″.72	34″.82	43″.97			
	0° 00′	58° 18′	185° 03′	359° 59′		0° 00′	58° 18′	185° 03′	359° 59′		
	00″.0	59″.2	10″.0	60″.0		00″.0	60″.9	10″.3	60″.0	2	5
		60″.9	09″.2	59″.9			62″.1	09″.2	59″.4	11	8
		*60″.05	09″.60	59″.95			61″.50	09″.75	59″.70		
		†60″.07	09″.62				61″.65	09″.90			
		0° 00′	126° 44′	359° 59′			0° 00′	126° 44′	359° 59′		
		00″.0	09″.0	60″.3			00″.0	09″.4	59″.9	3	6
			09″.0	59″.7				09″.7	59″.7	10	7
			*09″.00	60″.00				09″.55	59″.80		
			†09″.00					09″.65			

* *Observed mean.* † *Mean corrected for closure.*

Adjustment of Observations

The principle (1) of station adjustment was used to reduce the observations.

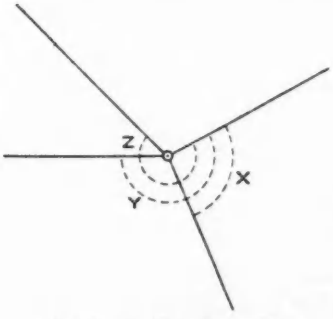


FIG. 5. *Independent angles measured.*

In Fig. 5 the measured angles are: x, y and z; $y-x$ and $z-x$; and $z-y$. From these measured values six observation equations connecting the three independent unknowns x, y and z can be formed, the solution of which by least squares gives the most probable (adjusted) values of the angles. The differences between the adjusted and measured values give six residuals from which the probable error of the measurement of the angle from two positions can be derived by means of the usual formula

$$r_2 = \pm 0.6745\sqrt{\frac{\Sigma v^2}{n-q}}.$$

The results for each night's observations with each theodolite are adjusted separately by the above method, and a comparison of the probable errors

gives the first basis for comparing the precision of measurements with each theodolite, as far as accidental errors are concerned.

The second basis of comparison is predicated on the *a priori* assumption that both instruments of a pair are capable of angular measurements of the same order of precision. This assumption was later found slightly erroneous. Hence it is assumed that the arithmetic mean or mean adjusted value of the measurements with two theodolites is the most probable value for that night. The differences between the measured and mean adjusted values give residuals from which probable errors are obtained for each theodolite by the employment of the above formula. The mean adjusted value of the angles is obtained by combining in one adjustment the six observation equations for each theodolite, together with three condition equations which require that the adjusted values of x, y and z from the two theodolites are equal.

The adjustment of the set in Table III and the calculation of the probable errors is given below in skeleton.

The observation equations are of the form

$$v = X_a - X_m + \Delta x \ ,$$

where X_a is the assumed value of any angle, X_m the measured value of the same angle, and Δx the most probable correction to the assumed value.

The condition equations which equalize the adjusted values for each theodolite are of the form

$$X_a + \Delta x = X_a + \Delta x'$$

or

$$\Delta x = \Delta x'$$

These condition equations are applied to the normal equations.

The numerical work of reducing the set in Table III is given in Table IV.

TABLE IV

CALCULATION OF ABSOLUTE TERMS

Symbol	Measured angles (seconds only)		Assumed value	Assumed − measured	
	Cooke	Kern		Cooke	Kern
x	34″.20	34″.72	34″.20	0″	−0″.52
y	34″.20	34″.82	34″.20	0″	−0″.62
z	44″.35	43″.97	44″.35	0″	+0″.38
$y-x$	60″.07	61″.65	60″.00	−0″.07	−1″.65
$z-x$	09″.62	09″.90	10″.15	+0″.53	+0″.25
$z-y$	09″.00	09″.65	10″.15	+1″.15	+0″.50

The observation equations and the condition equations are shown in tabular form in Table V.

TABLE V

SET-UP OF OBSERVATION AND CONDITION EQUATIONS

Cooke			Kern			
Δx	Δy	Δz	$\Delta x'$	$\Delta y'$	$\Delta z'$	l
Observation equations						
+1						0 $= v_1$
	+1					0 $= v_2$
		+1				0 $= v_3$
−1	+1					−0.07 $= v_4$
−1		+1				+0.53 $= v_5$
	−1	+1				+1.15 $= v_6$
			+1			−0.52 $= v_7$
				+1		−0.62 $= v_8$
					+1	+0.38 $= v_9$
			−1	+1		−1.65 $= v_{10}$
			−1		+1	+0.25 $= v_{11}$
				−1	+1	+0.50 $= v_{12}$
Condition equations						
+1			−1			+0 = 0
	+1			−1		+0 = 0
		+1			−1	+0 = 0

The resulting normal equations to effect the desired corrections to the assumed value of the angles are shown in Table VI. K_1, K_2, and K_3 are undetermined multipliers.

TABLE VI

NORMAL EQUATIONS

Δx	Δy	Δz	$\Delta x'$	$\Delta y'$	$\Delta z'$	K_1	K_2	K_3	
+3	−1	−1				+1			−0.46
	+3	−1					+1		−1.22
		+3						+1	+1.68
			+3	−1	−1	−1			+0.88
				+3	−1		−1		−2.77
					+3			−1	+1.33
						0			0
							0		0
								0	0

The first basis of comparison is obtained by solving the normal equations exclusive of the three condition equation columns at the right. By this process the corrections to the assumed values are obtained for each theodolite separately:—

$\Delta x = +0''.115$ $\quad$ $\Delta x' = -0''.030$
$\Delta y = +0''.305$ $\quad$ $\Delta y' = +0''.883$
$\Delta z = -0''.420$ $\quad$ $\Delta z' = -0''.092$

from which are obtained

$\Delta y - \Delta x = +0''.190$ $\quad$ $\Delta y' - \Delta x' = +0''.913$
$\Delta z - \Delta x = -0''.535$ $\quad$ $\Delta z' - \Delta x' = -0''.062$
$\Delta z - \Delta y = -0''.725$ $\quad$ $\Delta z' - \Delta y' = -0''.975$

With these data Table VII may be prepared.

TABLE VII

CALCULATIONS OF RESIDUALS FOR FIRST BASIS OF COMPARISON

Symbol	Assumed value	Adjusted values		Measured values		Adjusted − measured	
		Cooke	Kern	Cooke	Kern	Cooke	Kern
x	34″.20	34″.31	34″.17	34″.20	34″.72	+0″.11	−0″.55
y	34″.20	34″.50	35″.08	34″.20	34″.82	+0″.30	+0″.26
z	44″.35	43″.93	44″.26	44″.35	43″.97	−0″.42	+0″.29
$y-x$	60″.00	60″.19	60″.91	60″.07	61″.65	+0″.12	−0″.74
$z-x$	10″.15	09″.62	10″.09	09″.62	09″.90	0″	+0″.19
$z-y$	10″.15	09″.43	09″.18	09″.00	09″.65	+0″.43	−0″.47
						$\Sigma v^2 = 0''.4778$	1″.2588

$$r_2 \text{ (Cooke)} = \pm 0.6745\sqrt{\frac{0.4778}{6-3}} = \pm 0''.269$$
$$r_2 \text{ (Kern)} = \pm 0''.437$$

The second basis of comparison is obtained by solving the normal equations inclusive of the three condition equation columns. By this method the following values of the corrections to the assumed values are found:—

$$K_1 = +0''.669\ , \quad \Delta x = +0''.043 = \Delta x'$$
$$K_2 = -0''.775\ , \quad \Delta y = +0''.594 = \Delta y'$$
$$K_3 = -0''.275\ , \quad \Delta z = -0''.256 = \Delta z'$$

from which are obtained

$$\Delta y - \Delta x = +0''.551 = \Delta y' - \Delta x'$$
$$\Delta z - \Delta x = -0''.299 = \Delta z' - \Delta x'$$
$$\Delta z - \Delta y = -0''.850 = \Delta z' - \Delta y'$$

Table VIII may now be prepared.

TABLE VIII

CALCULATION OF RESIDUALS FOR SECOND BASIS OF COMPARISON

Symbol	Assumed values	Adjusted values	Measured values		Adjusted − measured	
			Cooke	Kern	Cooke	Kern
x	34″.20	34″.24	34″.20	34″.72	+0″.04	−0″.48
y	34″.20	34″.79	34″.20	34″.82	+0″.59	−0″.03
z	44″.35	44″.09	44″.35	43″.97	−0″.26	+0″.12
$y-x$	60″.00	60″.55	60″.07	61″.65	+0″.48	−1″.10
$z-x$	10″.15	09″.85	09″.62	09″.90	+0″.23	−0″.05
$z-y$	10″.15	09″.30	09″.00	09″.65	+0″.30	−0″.35
					$\Sigma v^2 = 0''.7906$	1″.5807

NOTE:—*It will be seen that the combined adjusted values above are the means of the corresponding adjusted values obtained by the separate adjustments in Table VII.*

$$r_2 \text{ (Cooke)} = \pm 0.6745\sqrt{\frac{0.7906}{6-3}} = \pm 0''.346$$
$$r_2 \text{ (Kern)} = \pm 0''.490$$

Results of Test

The nine parts with each of the three pairs of theodolites were adjusted as shown in the above example, and the probable errors (r_2) were as shown in Table IX.

TABLE IX

PROBABLE ERRORS (r_2) OF MEASUREMENT OF AN ANGLE (RESULTS IN ALL CASES ARE THE MEANS OF NINE PARTS)

Theodolite combination	Adjusted separately		Adjusted together	
Cooke-Kern	*Cooke* ±0″.31	*Kern* ±0″.42	*Cooke* ±0″.45	*Kern* ±0″.53
Cooke-Wild	*Cooke* ±0″.27	*Wild no. 551* ±0″.33	*Cooke* ±0″.38	*Wild no. 551* ±0″.41
Kern-Wild	*Kern* ±0″.35	*Wild no. 551* ±0″.27	*Kern* ±0″.50	*Wild no. 551* ±0″.43

NOTE:—*From the range of the nine probable errors of which each of the above is the mean, it is judged that the above probable errors may not be correct to within 0″.03.*

Conclusions from Field Test

(i) The probable errors derived from the adjustment of the measurements of each instrument separately indicate that the Cooke theodolite and Wild theodolite No. 551 measured angles equally precisely so far as accidental errors were concerned, while the measurements with the Kern theodolite were slightly less precise. The mean probable errors for the three instruments are:—

$$\text{Cooke theodolite} = \frac{0.31+0.27}{2} = \pm 0''.29$$

$$\text{Kern theodolite} = \frac{0.42+0.35}{2} = \pm 0''.39$$

$$\text{Wild theodolite No. 551} = \frac{0.33+0.27}{2} = \pm 0''.30$$

(ii) The mean probable errors for the three instruments when the measurements were adjusted in pairs are:—

$$\text{Cooke theodolite} = \frac{0.45+0.38}{2} = \pm 0''.42$$

$$\text{Kern theodolite} = \frac{0.53+0.50}{2} = \pm 0''.51$$

$$\text{Wild theodolite No. 551} = \frac{0.41+0.43}{2} = \pm 0''.42$$

The close relative agreement of these figures with those in (i) above shows that, while the first group did not reveal the full extent of the accidental errors, no systematic errors existed in any of the three theodolites which were not revealed by the first comparison.

(iii) The above conclusions substantiate those derived from laboratory tests with respect to Wild theodolite No. 551 and give considerable confidence that no systematic errors existed in this instrument which were not disclosed in the laboratory.

(iv) From a number of other considerations it seems likely that the slight inferiority of results with the Kern theodolite is due to graduation errors which naturally disclose themselves in such a test as the above where each part of the test is based on the mean of readings in only two positions of the circle. In a regular field program, where a much larger number of circle positions is employed, the effect of such graduation errors is practically eliminated. It is also to be noted that this instrument was originally provided with three micrometers, in which condition its field performance was quite satisfactory.

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